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Mass Transfer Effects in CO$_2$ Reduction on Cu Nanowire Electro catalysts

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Significant interests have risen in the development of catalytic nanomaterials for the electroreduction of CO$_2$. While extensive studies have been reported on tuning of surface structures to improve the chemical kinetics, less attention has been paid to the mass transfer effects in the CO$_2$ reduction reaction on nanoscale electrocatalysts. We report here an extensive study of CO$_2$ electroreduction on highly dense Cu nanowires, with the focus placed on practical high-flux conditions. Mass transfer effects are found to play an important role in this case, giving rise to diffusion-limited CO$_2$ reduction activity and selectivity. By correlating the observed transport phenomena to the CO$_2$ conversion rate calculated from the experimental data and the surface concentration of CO$_2$ on the nanowires, revealed by modeling, we find that the CO$_2$ reduction at large current densities. Our work emphasizes the necessity of considering mass transfer effects in the design of advanced electrocatalysts for CO$_2$ reduction as well as for understanding their structure-performance relationships.

Introduction

Electrochemical reduction of carbon dioxide (CO$_2$) has garnered increasing interest as a promising solution for artificial carbon recycling and solar-fuel conversion.$^{1-3}$ With water as the proton source, this process can convert the greenhouse gas, CO$_2$, into carbon monoxide, methane, ethanol, ethylene or other (oxygenated) hydrocarbons; e.g., CO$_2$ + H$_2$O + 2e$^-$ → CO + 2OH$^-$ and 2CO$_2$ + 8H$_2$O + 12e$^-$ → C$_2$H$_4$ + 12OH$^-$. These species can either be directly used as fuels, such as ethanol for substitution of gasoline, or fed into chemical plants to make more valuable products (e.g., various polymers from ethylene). Despite the great potential, electrochemical reduction of CO$_2$ has been challenged by the lack of efficient electrocatalysts. Even copper (Cu), the most active metal for reducing CO$_2$ to hydrocarbons known to date, still requires highly negative potentials of about -1.0 V versus reversible hydrogen electrode (RHE; the same in the following discussion) to produce valuable products such as ethylene and ethanol.$^{4-6}$ Additionally, the undesired byproduct, hydrogen, is still produced at significant amounts.$^{5,7}$

Ex tensive studies on Cu-based electrocatalysts have shown that the catalytic activity and product distribution are dependent on the electrode morphologies,$^{8-12}$ compositions,$^{13,14}$ and surface structures.$^{15-21}$ Besides the catalytic structure, electrocatalysis of CO$_2$ is also depend ent on the electrolyte and CO$_2$ partial pressure.$^{5,22-26}$ While protons are readily available in aqueous solutions via water reduction, the supply of reactant to the electrode surface is limited by the concentration and diffusivity of dissolved CO$_2$ molecules, which places a hurdle on the current density and efficiency of CO$_2$ reduction.$^{12,24}$ Moreover, the reduction of CO$_2$ and evolution of H$_2$, produces hydroxide anions (OH$^-$) and raises the high local pH on the electrode surface. The high local pH near the electrode surface could be detrimental to electrolysis of CO$_2$, as it shifts the equilibrium of CO$_2$ hydrolysis toward (bi)carbonates and further reduces the flux of CO$_2$ molecules attainable by the catalyst surface.$^{22,26}$ The early work on polycrystalline Cu electrodes (Cu-poly, in 0.1 M KHCO$_3$) by Hori et al. shows monotonic increase of Faradaic efficiency (FE) for CO$_2$ reduction, namely decrease of FE$_{H_2}$, in the potential region from -0.4 to -1.1 V, but a more recent study on Cu-poly (also in 0.1 M KHCO$_3$) by Jaramillo et al. reveals that the FE of hydrogen evolution (FE$_{H_2}$) reaches a minimum at ca. -1.1 V and then increase at more negative potentials.$^{27}$

The minimum in FE$_{H_2}$ or maximal FE$_{CO_2}$ is likely a result of the interplay between chemical kinetics on the surface and transport of CO$_2$ toward the catalyst surface: in the low-overpotential region, the electrocatalytic performance is more determined by the kinetic competition of the CO$_2$ reduction and hydrogen evolution reaction pathways, with the former becoming more favorable at more negative potentials; on the other side, mass transfer plays a more important role at more elevated overpotentials and places a limit on the efficiency of CO$_2$. 

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reduction.\textsuperscript{22,24,30} However, it is noticed that most of the previous discussions on mass transfer and local pH effects are based on electrocatalytic studies at fixed potentials \textsuperscript{5,23,24,26} and/or with low-surface-area (e.g., extended-surface) electrodes.\textsuperscript{3,22,24-26} It largely remains elusive how the mass transfer effects correlate to the nanostructures of high-surface-area electrocatalysts, where the supply of CO\textsubscript{2} could play a more vital role in determining the catalytic performance owing to the large current densities.\textsuperscript{8,10,12,31}

Here we report on the investigation of mass transfer effects in CO\textsubscript{2} reduction by using highly dense Cu nanowires as the electrocatalysts. The Cu nanowires were synthesized by reducing CuO nanowires grown on Cu mesh, either by applying a cathodic electrochemical potential or by thermal annealing in the presence of hydrogen. Our previous reports have shown that the electrochemically reduced Cu nanowires are highly active for CO\textsubscript{2} reduction, favoring the production of CO and formate at potentials more positive than -0.5 V.\textsuperscript{10,32} In this work, we aim to systematically study the reduction of CO\textsubscript{2} in the high-overpotential region, i.e., potentials more negative than -0.5 V, where the transport phenomena become more pronounced compared to lower overpotentials. The dependence of catalytic activity and selectivity on the electrode potential are systematically evaluated on three types of Cu nanowires with different dimensions and surface roughness factors. The catalytic performance of each catalyst is correlated to the CO\textsubscript{2} conversion rate calculated from the experimental data and the surface concentration of CO\textsubscript{2} on the nanowires derived from transport modeling, where the effects of mass transfer on CO\textsubscript{2} reduction electrocatalysis are discussed.

**Experimental**

**Synthesis of Cu Nanowires.** Cu grid (100 mesh) was washed in 0.1 M HCl and then several times in DI H\textsubscript{2}O. After drying in vacuum, the mesh was treated at 585-600 °C in air for 8 hours. Electrochemical reduction at ~0.4 V was used to convert CuO nanowires to Cu nanowires. Reduction of CuO was monitored by recording the cathodic current and was deemed complete when a steady state current had been achieved.\textsuperscript{15} Forming gas reduced nanowires (FGR) were synthesized by annealing CuO nanowires at 150 °C for 15h (HR-150) and 300 °C for 15h (HR-300 (15h)) while passing 10 sccm 5% H\textsubscript{2}/Ar through a gas tube. The complete reduction of each sample was verified by X-ray diffraction (XRD) post reduction treatment (Figure S1).

**Material Characterization.** SEM images were collected on a JEOL JSM-6700F field-emission scanning electron microscope. A field-emission Philips CM300-FEG (300 kV) was used for TEM imaging. XRD patterns were collected on a PANalytical X’pert Powder X-Ray Diffractometer equipped with a Cu K\textsubscript{α} source (λ=0.15406).

**Electrochemical Studies.** The electroreduction of CO\textsubscript{2} was studied in 0.1 M KHCO\textsubscript{3} using a liquid and gas-tight custom-made electrolysis cell equipped with an Autolab 302 potentiostat (Metrohm). The electrolyte was purged with CO\textsubscript{2} at a rate of 20 sccm for 10 minutes prior and throughout the 1-hour duration of the measurement. To prevent oxidation of products at the anode, an anion exchange membrane from Selemion was used to separate the two compartments. The reference electrode (Ag/AgCl from BASI) was located in the cathode compartment. A piece of Pt mesh was used as the counter electrode in the anode compartment. Gas products were sampled periodically via a gas chromatography coupled to a mass spectrometer (Shimadzu GCMS-QP2010 SE). This method has relatively large uncertainty for measuring the concentration of H\textsubscript{2}. The previous study has shown that the uncertainty in FE\textsubscript{H2} can be up to ~10%.\textsuperscript{10} Liquid products were analyzed at the end of each potential by collecting an aliquot of the electrolyte and using nuclear magnetic resonance (NMR, Bruker Advance 300 MHz) spectroscopy. An 85% IR drop correction was implemented via Autolab software.

Double-layer capacitance was measured to estimate the surface roughness and electrochemically active surface area (ECSA) of the Cu nanowires by recording cyclic voltammograms (CVs) in a non-Faradaic potential region (Figure S2).\textsuperscript{10} The capacitances were compared and standardized versus a polycrystalline Cu disk to derive the surface roughness factors (Table S1).\textsuperscript{8} The current densities per geometric area of the electrode \(j_{\text{tot}}\) and \(j_{\text{CO2}}\) were divided by the surface roughness factor to find out the specific activities (e.g., \(j_{\text{tot}}\) and \(j_{\text{CO2}}\)) as discussed in the text.

**Results and Discussion**

Figure 1 presents the electron microscopy images of the three types of Cu nanowires employed in this study, including one prepared by electrochemical reduction (~0.4 V) at room temperature and two prepared by reduction in H\textsubscript{2} at 150 and 300 °C (denoted as ECR, HR-150 and HR-300, respectively). The ECR nanowires have typical diameters in the range of 50-100 nm and lengths of up to 50 μm (Figure 1 a-c). The HR-150

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**Figure 1.** Electron microscopy images of (a-c) ECR, (d-f) HR-150 and (g-i) HR-300 Cu nanowires prepared by reduction of CuO nanowires pre-grown on Cu mesh. The first and second columns are the SEM images, and the right column is TEM images.
nanowires have similar lengths to the ECR nanowires, but slightly larger diameters of 100-120 nm (Figure 1 d-f). The nanowires prepared at 300 °C have diameters of ≥200 nm and about 20 μm in length (Figure 1 g-i). The larger diameters and shorter lengths of the nanowires prepared at higher temperatures are likely due to thermally driven atomic diffusion and growth of crystalline domains. Corresponding to the nanowire dimensions, the surface roughness factors are estimated to be 356, 145 and 23 (in reference to extended surfaces of polycrystalline Cu electrodes) for the ECR, HR-150 and HR-300 nanowires, respectively, by electrochemical capacitance measurements (see the Experimental methods). It should be pointed out that the smaller roughness factors of the nanowires prepared at higher temperatures may not only be a result of the change in dimensions, but also due to surface smoothing during the thermal reduction treatment.

The electroreduction of CO2 was studied in a custom-made gas cell containing 0.1 M KHCO3 electrolyte, with the gas- and liquid-phase products analyzed using gas chromatograph-mass spectrometry (GC-MS) and nuclear magnetic resonance (NMR) spectroscopy, respectively. In the high-overpotential region, the total electrode current density per geometric area (Jtot, Figure 2a) exhibits a nearly exponential increase as the potential becomes more negative. At -1.0 V, the ECR nanowires reach ~93 mA/cm2, compared to ~27 and ~5 mA/cm2 for the HR-150 and HR-300 nanowires, respectively. The trend in Jtot, ECR > HR-150 > HR-300, is consistent with the trend for surface roughness, suggesting that the different types of Cu nanowires would have rather similar specific activities, namely current density per electrochemically active surface area (ECSA) of Cu (Jsc, obtained by dividing Jtot with the surface roughness factor). Indeed, the specific activity is determined to be 0.26 and 0.24 mA/cm2 at -1.0 V for the ECR and HR-300 nanowires, respectively, while the HR-150 nanowires have a slightly lower value (0.18 mA/cm2 at -1.0 V) (Figure 2b).

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Figure 2. Total current densities generated by the Cu nanowires for CO2 reduction normalized by (a) the geometric area of the electrode and (b) the ECSA of Cu.

The three types of Cu nanowires exhibit distinct selectivities for CO2 reduction, with the product distribution dependent on the electrode potential (Figure 3). At -0.5 V, the ECR nanowires have FEs of 53% and 25% toward CO and formate (hydration product of CO), respectively (Figure 3a). CO and formate are also the dominant products from CO2 reduction on the HR nanowires at this potential, but the FEs of C1 species (CO + HCOOH) add up to be only 38% and 10% for the HR-150 and HR-300 nanowires, respectively (Figures 3b, c). As the potential becomes more negative, the selectivity increases for multi-carbon products (C2+, including ethylene, ethane, ethanol and 1-propanol), which is associated with the decrease of FEs toward C1 products, indicating that these (oxygenated) hydrocarbons are formed by further reduction of CO intermediates at elevated overpotentials. The HR-150 nanowires have the highest selectivity toward ethylene (FEEthylene, reaching ~21% at ~1.0 V, among the three types of nanowires and throughout the potential region studied here. In addition to these results, it is also noticed that the overall selectivity for CO2 reduction (FECO2, counting all the CO2 reduction products) of the HR-150 nanowires is rather consistent at ~40% throughout the potential region, whereas the ECR and HR-300 nanowires exhibit opposite trends in terms of FE CO2 when the potential is scanned from ~0.5 to ~1.0 V, i.e., decreasing from 82% to 18% for the ECR and increasing from 10% to 38% for the HR-300 nanowires (Figure 3d).

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Figure 3. Measured Faradaic efficiencies (FEs) towards the various products for a) ECR, b) HR-150, and c) HR-300 nanowires. (d) Comparison of total FE of CO2 reduction (FE CO2, counting all the carbon-containing products) for the three types of Cu nanowires.

Our previous work has shown that the nanowires prepared at lower temperatures (e.g., room temperature for the ECR) expose more open facets, such as (100) and (110) (likely also surface defects and stepped sites that are associated with grain boundaries) than those prepared at higher temperatures. The energy barriers are known to be lower for CO2 reduction and C-C bond formation on the open facets (or undercoordinated sites) than on close-packed (111) surfaces. The surface-structure sensitivity could thus explain the catalytic performances at relatively low overpotentials where the activity is kinetically limited, such as the trend of ECR > HR-150 > HR-300 for the FE of CO2 reduction at ~0.5 V (Figure 3d). At higher overpotentials where the current density becomes much larger (e.g., Jtot > 10 mA/cm2 at potentials more negative than ~0.6 V for the ECR nanowires, Figure 2a), it is believed that mass transfer effects play a more substantial role in determining the catalytic performance. For example, the lower FEs of CO2 reduction observed on the ECR nanowires compared to the HR-150 and HR-300 nanowires at ~1.0 V can’t be explained by the surface
structure effects (Figures 3a-c). Similarly, the decreasing total FE of CO\textsubscript{2} reduction and increasing production of H\textsubscript{2} as the potential becomes more negative observed on the ECR nanowires is hard to be interpreted in terms of kinetic effects, but more likely a result of transport limitations (Figure 3d). The finding that the HR-150 nanowires with an intermediate roughness factor possess the highest selectivity in the high-overpotential region resembles several previous reports on high-surface-area Cu catalysts,\textsuperscript{12,31,34} but explicit interpretations of mass transfer effects have not been seen for such nanostructured electrodes.

In the reported study of CO\textsubscript{2} reduction on Cu-poly electrodes, a minimal FE\textsubscript{CO} \textsubscript{2} (or maximal FE\textsubscript{CO}) is observed at ca. \(-1.1 \text{ V}\).\textsuperscript{27} As discussed above, it is likely that the interplay between chemical kinetics on the surface and the transport of CO\textsubscript{2} toward the catalyst has given rise to this volcano-type dependence of FE\textsubscript{CO} \textsubscript{2} on the electrode potential: on the right side of the peak, FE\textsubscript{CO} \textsubscript{2} increases (or equivalently, FE\textsubscript{H2} decreases) as the potential becomes more negative owing to the more favorable kinetics of CO\textsubscript{2} reduction than hydrogen evolution (associated with the increase of surface coverage of 4\textsuperscript{+}CO);\textsuperscript{20} on the left side of the peak, FE\textsubscript{CO} \textsubscript{2} decreases (or FE\textsubscript{H2} increases) at more negative potentials, owing to the limited mass transfer of CO\textsubscript{2} toward the catalyst surface at increasing current densities. The peak position is likely at \(-1.1 \text{ V}\) vs. RHE on Cu-poly, but can be dependent on the surface structures, which determines the kinetic competition between CO\textsubscript{2} reduction and hydrogen evolution, and spatial structure of the electrode, including morphology and porosity, as well as the partial pressure of CO\textsubscript{2} and the electrolyte, all of which have an effect on the transport of CO\textsubscript{2} during the reaction. By taking a close look at the electrocatalytic performance of the Cu nanowires (Figures 2a and 3), we further find that the peak position is closely related to the geometric current density of the electrode, which is associated with a current density in the range of \(5 - 10 \text{ mA/cm}^2\) \textsubscript{geo} (in the condition of 0.1 M KHCO\textsubscript{3}, saturated with CO\textsubscript{2} at \(\approx 1 \text{ atm}\)). This current density range corresponds roughly to the peak position of FE\textsubscript{CO} \textsubscript{2} at \(-0.5 \sim \sim -0.6 \text{ V}\) on the ECR nanowires, \(-0.6 \sim -0.7 \text{ V}\) for the HR-150 nanowires, and \(-1.0 \text{ V}\) for the HR-300 nanowires. Surprisingly, the current density identified here for the peak FE\textsubscript{CO} \textsubscript{2} matches the value observed in the case of Cu-poly, \(\approx 8 \text{ mA/cm}^2\) \textsubscript{geo} from the report by Jaramillo \textit{et al.}.\textsuperscript{27} This trend is unlikely to be a coincidence, especially considering the different morphologies and surface roughness factors of the two types of electrodes. The relation observed here may still be too preliminary to be claimed universal for CO\textsubscript{2} reduction (even under the given reaction conditions), considering the complexity in comprehensive understanding of the chemical kinetics and mass transfer on the nanostructured electrodes, but we believe it is an important feature of the CO\textsubscript{2} reduction on high-surface-area, nanostructured electrocatalysts and certainly deserves more detailed studies in the future.

To develop a more comprehensive understanding of the mass transfer effects in CO\textsubscript{2} reduction electrocatalysis, we have plotted the overall current densities of CO\textsubscript{2} reduction (excluding the partial currents toward hydrogen evolution) against the electrode potentials for the three types of Cu nanowires, both per geometric area of the electrode \((J_{\text{CO2}}\textsubscript{geo}, \text{Figure 4a})\) and per ECSA of Cu \((j_{\text{CO2}}\textsubscript{geo}, \text{Figure 4b})\). It can be seen that \(J_{\text{CO2}}\) exhibits a monotonous increase as the potential becomes more negative for all the three types of nanowires, following the order ECR > HR-150 > HR-300 throughout the potential region, which is consistent with the trend for roughness factors (Figure 4a). However, different situations are observed for the current densities per ECSA, where the ECR nanowires have the highest \(j_{\text{CO2}}\) at potentials more positive than \(-0.8 \text{ V}\) but the HR-150 nanowires outperform at more negative potentials (Figure 4b). The lower \(j_{\text{CO2}}\)\textsuperscript{geo} of the ECR nanowires at \(-0.9\) and \(-1.0 \text{ V}\) is clear indication of CO\textsubscript{2} diffusion limitation, which is well correlated to the lower FEs of this type of nanowires than the other two types for the reaction in this potential region (Figure 3).

We have recently developed a transport model for the CO\textsubscript{2} reduction reaction on Cu nanowire electrocatalysts.\textsuperscript{30} Compared to the previously reported simulations for planar electrodes,\textsuperscript{22} our model has taken into account the spatial distribution of reactions (including CO\textsubscript{2} reduction toward various products and hydrogen evolution) along the nanowires, by assuming a first-order dependence of the CO\textsubscript{2} reduction reaction activity on the local concentration of CO\textsubscript{2} and a linear increase of the hydrogen evolution reaction activity with the depth into the nanowires. This has allowed us to simulate the surface concentrations of chemical species and local pH along the nanowires at each potential (see the Supporting Information, section 3). Figure 5a summarizes the obtained CO\textsubscript{2} concentration \((\text{[CO}_2\text{]}_{\text{sppace}}\) on the electrode surface (base of the nanowires) at various potentials, taking into account the nanowire lengths. It can be seen that, for the three types of Cu nanowires, \([\text{CO}_2\text{]}_{\text{sppace}}\) decreases as the potential becomes more negative, with the magnitude of the drop below the bulk value following the trend ECR > HR-150 > HR-300. In particular, it approaches zero at \(-0.9 \text{ V}\) on the ECR nanowires. The complete depletion of CO\textsubscript{2} on the electrode surface at the high-overpotential limit, or more relevantly, the large current density (ca. \(>15 \text{ mA/cm}^2\) \textsubscript{geo}, Figure 4a), is indicative of the diffusion limitation, as confirmed by the observation of a plateau in the CO\textsubscript{2} conversion rate, calculated from the experimental data, in this potential region (Figure 5b, see more details of the calculation in the Supporting Information, section 4). The observation that the FEs of CO\textsubscript{2} reduction drop as the potential becomes more negative for the
ECR nanowires (Figure 3a) can thus be attributed to the evolution of more hydrogen as the reaction approaches or goes beyond the diffusion limitation of CO$_2$. In contrast, the surface concentration of CO$_2$ on the HR-300 nanowires is nearly the same as in the bulk electrolyte, indicating that the reaction is not limited by CO$_2$ diffusion and the conversion for CO$_2$ flux is low in this case. The HR-150 nanowires display more CO$_2$ depletion than the HR-300, but does not reach complete depletion of CO$_2$ even at -1.0 V. These results explain the observed trends for FE$_{CO_2}$ in Figure 3d, namely the rather consistent total selectivity for CO$_2$ reduction throughout the potential region for the HR-150 nanowires, whereas the ECR and HR-300 nanowires exhibit opposite trends. It is noticed that the trapping of gaseous species (e.g., CO) inside porous electrocatalysts has been reported to be beneficial for enhancing the selectivity toward C$_2$ products, due to the increased residence time of reaction intermediates.$^{12,35}$ If the Cu nanowires also possess such a trapping effect (which remains unclear), the HR-150 nanowires with an intermediate roughness could have also reached a balance between the supply of CO$_2$ and the retention of intermediates for the reaction, giving rise to the highest selectivity toward ethylene at the high-overpotential (or, large-current density) conditions.

From the above discussion, we can see that the mass transfer effects place a physical limitation on the rate of CO$_2$ conversion on the nanowire electrocatalysts. This value is determined to be $\sim 35$ nmol s$^{-1}$ cm$^{-2}$ geo and $\sim 0.10$ nmol s$^{-1}$ cm$^{-2}$ Cu from the calculated CO$_2$ conversion rates (Figures 5b and c). It should be pointed out that the theoretical diffusion limit is estimated to be ca. 113 nmol s$^{-1}$ cm$^{-2}$ according to the Fick’s law, as determined by the concentration and diffusivity of CO$_2$ in the electrolyte (see section 3 in the Supporting Information). This theoretical limit corresponds to $\sim 0.32$ nmol s$^{-1}$ cm$^{-2}$ Cu considering the roughness factor (356) of the ECR nanowires. The smaller values of maximal CO$_2$ conversion rates seen from the electrocatalytic studies suggest that the diffusion of CO$_2$ through the Cu nanowires may also be subjected to other restrictions, such as the higher local pH in the space among the nanowires that has reduced the concentration of dissolved CO$_2$. Similar arguments could also be made for the complete depletion of CO$_2$ at the base of the ECR nanowires at high overpotentials (as mentioned above), namely the attainability of CO$_2$ on the electrode surface may not only be limited by the reaction and consumption of CO$_2$ along the nanowires, but also by the rise of local pH that has further attenuated the supply of CO$_2$. Compared to the ECR nanowires, the HR-150 nanowires have a lower CO$_2$ conversion rate of $\sim 25$ nmol s$^{-1}$ cm$^{-2}$ geo at -1.0 V (Figure 5b). This indicates that an even higher $J_{CO_2}$ could be reached by the HR-150 nanowires if the potential is more negative than -1.0 V. The HR-300 nanowires have the highest CO$_2$ conversion rate per ECSA, reaching 0.28 nmol s$^{-1}$ cm$^{-2}$ Cu at -1.0 V (Figure 5c). Considering that the HR-300 nanowires have the lowest roughness factor in the series, their higher specific activity ($j_{CO_2}$, Figure 4b) at this potential is simply a result of being less limited by CO$_2$ diffusion, instead of indicating the presence of more active sites or higher turnover rates.

**Conclusions**

In summary, we have studied the electroreduction of CO$_2$ on high-surface-area Cu electrocatalysts. At the relatively high overpotentials (from -0.5 to -1.0 V), mass transfer is found to play an important role in determining the electrocatalytic performance owing to the large current densities (ca. -1 – -100 mA/cm$^2$). The limited supply of CO$_2$ places an upper limit on the CO$_2$ conversion rate and causes a drop in Faradaic efficiency for CO$_2$ reduction at large current densities. As a result, the Cu nanowires with intermediate surface roughness (HR-150) has the best performance among the three types of high-surface-area electrocatalysts investigated here. Our work highlights the importance of taking transport into account in the design of high-performance electrodes for CO$_2$ reduction.

**Conflicts of interest**

There are no conflicts to declare.
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Notes and references

Mass Transfer Effects in CO$_2$ Reduction on Cu Nanowire Electrocatalysts

Table of Content

Mass transfer effects play an important role in CO$_2$ electroreduction, giving diffusion-limited activity and selectivity on Cu nanowire electrocatalysts.

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