



# Probing the reactive intermediate species generated during electrocatalysis by scanning electrochemical microscopy

Jean-Marc Noël, Frédéric Kanoufi

## ► To cite this version:

Jean-Marc Noël, Frédéric Kanoufi. Probing the reactive intermediate species generated during electrocatalysis by scanning electrochemical microscopy. *Current Opinion in Electrochemistry*, 2022, 35 (24), pp.101071. <10.1016/j.coelec.2022.101071>. <hal-03816543>

**HAL Id: hal-03816543**

**<https://hal.science/hal-03816543v1>**

Submitted on 16 Oct 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

## Highlights

- Scanning electrochemical microscope to probe short lifetime reactive intermediate species.
- Detection of reactive intermediates involved in electrocatalytic processes.
- Adsorbed and dissolved reactive intermediates detected by various SECM methodologies
- Multiscale approach: from micro to nanometer scales.
- Numerical simulation to quantify the intermediates production and reactivity.

# Probing the reactive intermediate species generated during electrocatalysis by scanning electrochemical microscopy

Jean-Marc Noël\* and Frédéric Kanoufi

Université Paris Cité, ITODYS, CNRS, F-75013 Paris, France

\*Corresponding author: jean-marc.noel@u-paris.fr

## Abstract:

Reactive intermediate species (RIS) are of major importance in many chemical and biological reactions. Due to the high reactivity their presence are usually confined at the place of their formation. Whereas electrochemical tools can electrogenerate them through various mechanistic paths, the local electrochemical probes, such as a micro/nanoelectrode tip of the scanning electrochemical microscopy (SECM), are by essence well adapted to catch their formation and reactivity at the location of their production. This review presents the recent local electrochemical probe strategies employed to probe RIS down to the nanometer scale, either immobilized on the surface of an electrode or within a reaction layer, in solution. It is illustrated by examples borrowed from the field of electrocatalysis, with emphasis on the contributions of numerical simulation to derive quantitative information.

**Keywords:** Scanning electrochemical microscopy, reactive intermediate species, nanoelectrochemistry, numerical simulation.

## Introduction

Reactive intermediate species (RIS) are key species involved in many chemical [1,2] and biological processes [3], and whereas their production must be encouraged in some applications, in others they must be avoided. In any case, a complete understanding of their formation as well as their quantification is needed. ESR (Electron Spin Resonance Spectroscopy) and chromatography are powerful methods to detect radical species trapped by conventional radical scavengers, including those electrochemically generated [1,4,5]. However, they are mostly limited to indirect detection and remain inoperative for local or time-resolved analysis. Alternatively, Raman spectroscopy, at different nanostructured surfaces for enhanced electromagnetic field, offers operando detection of RIS, but remains limited to surface-adsorbed reactive species with sub-second time resolution [6,7]. Due to their short lifetime,  $\tau$  in the sub-ms to sub- $\mu$ s, electroanalytical tools allowing to probe them at the earliest stage of their formation are needed. This can be performed by ultra-fast electrochemistry [8], although often difficult to implement and limited to electroactive intermediates.

Alternatively, RIS could be detected by electrochemical probes with size comparable to the characteristic distance they could travel  $\delta \approx (D\tau)^{1/2}$ , with  $D$  the diffusion coefficient of the RIS. Such small electrochemical probes, mostly used in the scanning electrochemical microscope (SECM) configuration, i.e. the probe facing a reacting interface, can then collect and/or identify RIS in a confined space nearby the location of their production [9].

Herein we review the different SECM methodologies employed to specifically probe molecular RIS either adsorbed at a surface or generated in the reaction layer of an electrode, in the context of molecular electrocatalysis.

## SECM modes used for the detection of reactive intermediate species

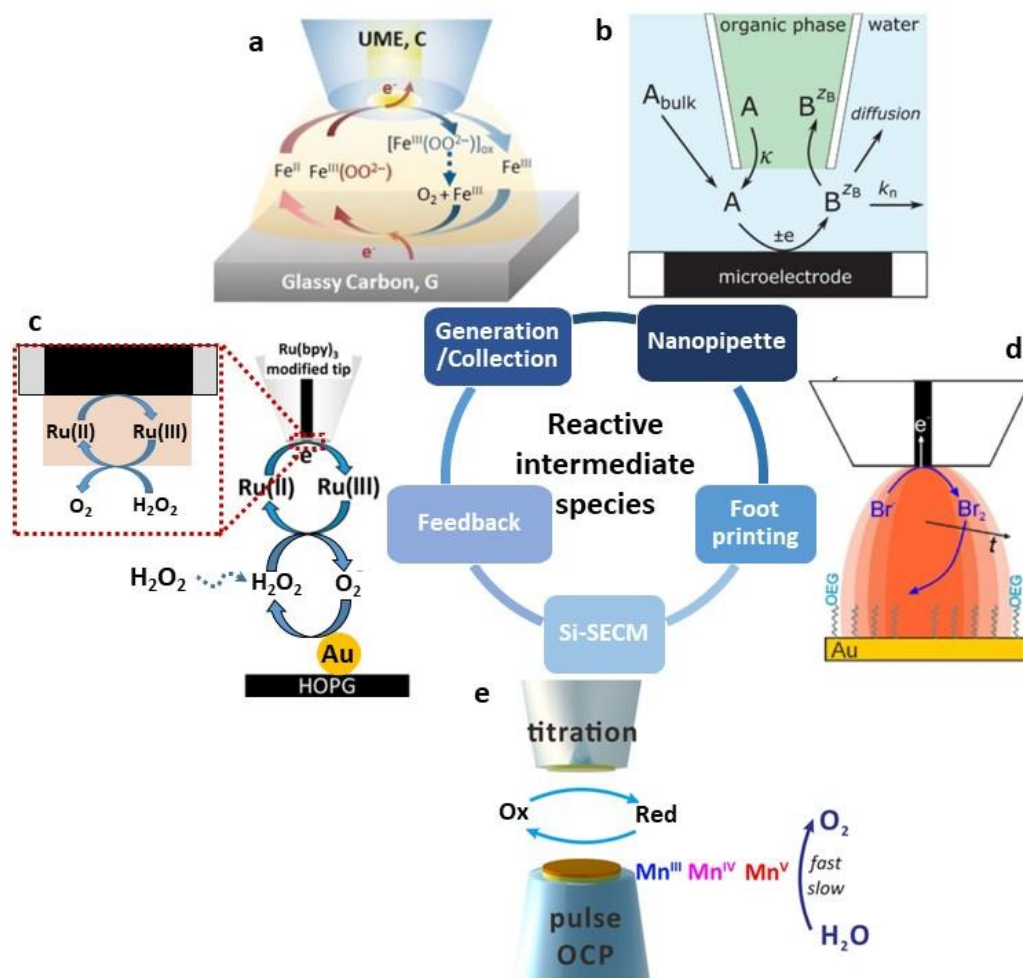
This section first presents the different modes of the SECM employed to identify and quantify various RIS generated in solution. Electroactive RIS are more often probed directly, where they are created using the generation collection mode (G/C) of the SECM. In this mode, inherited from the ring-disk electrode configuration, a generator electrode, G, triggers a reaction of interest while the collector one, C, facing G, collect the RIS produced at G. Figure 1a illustrates the substrate generation/tip collection (SG/TC) of  $\text{Fe}^{\text{III}}(\text{OO}^{2-})$  intermediates of ms lifetime produced during  $\text{O}_2$  reductive activation at iron porphyrins [10]. The reverse configuration (tip generation, substrate collection mode, TG/SC) was also employed with gap distances from 10  $\mu\text{m}$  to 500 nm, using a classical or an hemispherical UME [11], or even down to 73 nm employing nanoelectrodes (nanoSECM) [12]. In such a configuration,  $\tau \sim 1 \mu\text{s}$  to  $\sim 10 \text{ ns}$  lifetime RIS were directly probed [11,12]. However, the gap between the generator and the collector cannot be below  $\sim 3 \text{ nm}$  due to the direct electron tunneling occurring below this limit [13,14].

To push the detection of even shorter lifetime RIS, an elegant approach proposed to replace nanoelectrodes by a nanopipette filled with an organic phase, immiscible with the external aqueous solution, and to use it as a SECM tip (Figure 1b) [15–17]. The nanopipette delivers an electroactive species, A, to a polarized substrate that in turns electrogenerate the reactive intermediate, B,

subsequently transferred and collected in the nanopipette phase. Theoretical developments evidenced that extremely unstable RIS, with  $\tau \sim 1$  ns scale lifetime, require cyclic voltammetry collection at  $> 10^5$  V/s scan rates [15,18]. This nanopipette strategy can be useful for the detection and identification of many charged intermediates, electroactive or not, in both aqueous and nonaqueous solutions.

Indirect SECM detection modes have been also proposed, for example to probe non-electroactive RIS. The SECM feedback mode is one such powerful technique to quantitatively analyze electrochemical processes involving RIS. In this mode, RIS are detected indirectly through the use of a redox catalytic loop between a redox mediator activated by the SECM tip and the RIS present in the solution, as illustrated in Figure 1c for the feedback detection of  $\text{H}_2\text{O}_2$  from its oxidation by  $\text{Ru}^{\text{III}}$ . Even though  $\text{H}_2\text{O}_2$  is not strictly speaking a RIS, the strategy proposed could apply equivalently to RIS detection. The RIS ( $\text{H}_2\text{O}_2$ ) generated from a reaction of interest (either in the bulk or from a catalytically active NP) is revealed from its homogeneous reaction with a tip-electrogenerated redox mediator ( $\text{Ru}^{\text{III}}$  from a  $\text{Ru}^{\text{II}}$  solution in Figure 1c). This catalytic loop, often analyzed as an  $\text{EC}'$  mechanism, is probed by the catalytic tip current recorded for the redox mediator conversion [19–23]. It is sensitive to mass transfer of the RIS to the tip, which is controlled by the volume between the tip and an interface (either surface [21] or liquid/liquid [20]). The RIS are often detected experimentally by performing approach curves (variation of the tip-interface distance) and their concentration and lifetime can be quantified with the help of numerical simulation of the complex homogeneous reactions involved in the process [20,21]. The SECM tip can also work at fixed distance from the interface, in this case reactive intermediates with  $\tau$  in the ms range can be detected from current transients [19,23] or CVs [22]. To assess more unstable RIS and reach reaction occurring at the nanometer scale, a recent strategy proposed to confine the redox moieties in a thin layer coating the SECM tip, as illustrated in the inset of Figure 1c [24,25]. It further allows imaging indirectly the specific (electro)regeneration of the RIS at individual nanoparticles, as illustrated in Figure 1c [25].

Noteworthy, the G/C mode can also exploit such indirect detection of RIS produced from a substrate using a redox mediator either dissolved in the bulk, [26] or immobilized on the SECM tip (analogously to Figure 1c) [25]. This strategy was used to image the production of RIS both at the micrometer [26] and at the nanometer scale [25].



**Figure 1.** Illustration of the different SECM modes employed to investigate reactive intermediate species. a) generation/collection adapted from Ref. [10], b) nanopipette adapted from Ref. [15], c) feedback adapted from Ref. [24], d) foot printing adapted from Ref. [31] and e) surface interrogation adapted from Ref. [45].

Footprinting analysis (Figure 1d) is another indirect powerful methods to analyze local (electro)chemical reactions. A reactive footprint is performed by exposing a substrate modified by an organic coating [27,28] or self-assembled monolayers [29–32] to reactive intermediates, etchants, electrogenerated by a SECM tip. The reactivity between the reactive etchant and the organic layer leads most of the time to its irreversible local transformation (often destruction) producing a pattern with contrasted chemical functionalities. The footprint can be imaged post-mortem (SECM, AFM, condensation...) or operando (during its formation) using optical monitoring [33]. This methodology allows evidencing the bulk formation of reactive species [28] and to quantitatively characterize their reactivity with the layer [30–32] by analyzing the footprint expansion and/or width with the local electrogeneration time. It also allows studying competing reactions of the etchant or the layers with species present in solution such as radical scavengers [32]. Besides, this footprinting strategy can be exploited to develop methodologies and tools for the electrochemical micro/nanomachining of surfaces [34–36]. Noteworthy, the degradation of a layer deposited on the SECM tip by substrate-generated RIS is possible [33].

Finally, the SECM in the surface interrogation, SI, mode, illustrated in Figure 1e was widely employed to identify the formation of surface-bound RIS during photo(electro)chemical [37–40] or

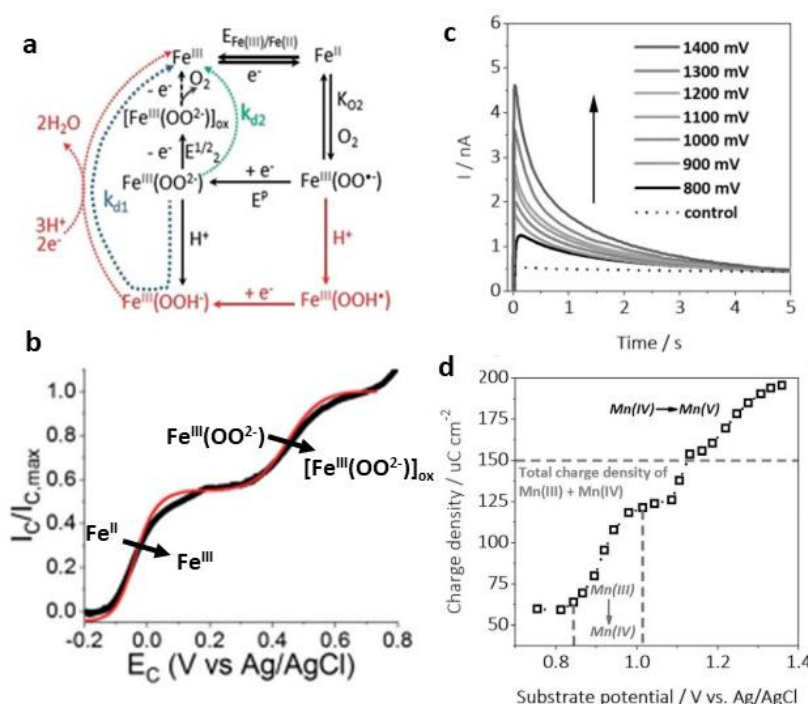
electrocatalytic processes [41–45]. Briefly, the SI-SECM operates in a transient feedback mode between two electrodes of comparable sizes. For instance, Figure 1e explores the ability of high-valent Mn oxides to catalyse the oxidation of water produced by a short oxidation potential pulse at a Mn-oxide substrate. While the substrate potential is returned to open circuit potential, the SECM tip, kept typically  $\sim 1\ \mu\text{m}$  from the substrate, generates a titrant species (a redox mediator present in solution) which diffuses towards and reacts chemically (here is overall oxidized) with the surface species produced during the first step [44]. The SECM tip then provides a transient feedback current until the adsorbate has been entirely consumed. With the help of finite element simulation, such transient response yields the surface concentration of the reactive adsorbate. By carefully choosing the titrant redox potential, one can evidence the formation of different populations of surface RIS [41,45]. The SI-SECM can operate in cyclic voltammetry [41] to detect moderately RIS while chronoamperometry [37,39–46] grants access to highly RIS with ca.  $1\ \mu\text{s}$  lifetime [42,43,45].

## Applications to electrocatalytic reactions

The different SECM modes described above were used to evidence the formation of many different RIS produced during various electrochemical processes. This is the case of reactive oxygen species (ROS) issued from the oxygen reduction reaction (ORR). For instance highly unstable superoxide ( $\text{O}_2^{\bullet-}$ ) ion in neutral pH aqueous media was evidenced [16]. It corresponds to 9% of the oxygen species reduced at Pt electrode, whereas its half-life was evaluated to be  $\sim 2\ \mu\text{s}$ . Besides, the formation of very reactive hydroxyl radicals ( $\text{HO}^\bullet$ ) during the ORR on Prussian blue film [33], or on Pt microelectrode could be indirectly evidenced [28]. The production of  $\text{HO}^\bullet$ , also confirmed on Pt materials by EPR [4,47], may explain the nanoscale dissolution of Pt often observed during the ORR [48,49]. This very reactive intermediate was also identified indirectly during the ORR mediated, in a Fenton-like reaction, by a  $[\text{Cu}(\text{2CP-Bz-SMe})]^{2+}$  complex adsorbed on a gold surface [26]. ORR can also be triggered by organometallic complexes. It rather involves ROS in the form of adducts (as ligands of the metallic center). In the case of the reductive activation of  $\text{O}_2$  by Fe porphyrins in organic media (Figure 2A) [10], the SECM could only directly probe and quantify the  $\text{Fe}^{\text{III}}(\text{OO}^{2-})$  intermediates electrogenerated during the oxygen activation mechanism. Further numerical simulation of the LSV obtained at the SECM tip (red curve, Figure 2a), allowed extracting pertinent thermodynamic and kinetic parameters describing the overall catalytic cycle. With different ring-substituted porphyrin, such strategy offers structure–activity rationalization of the catalytic  $\text{O}_2$  activation in agreement with earlier DFT calculations [50]. By extension this strategy should be useful to study the different electrochemical activation pathways of small molecules ( $\text{O}_2$ ,  $\text{N}_2$ ,  $\text{NH}_3$ ,  $\text{CO}_2$ ).

Reactive radical intermediates are also involved in many complex redox catalytic reactions such as Belousov-Zabotinsky oscillating reactions[21] or electro-chemiluminescence (ECL) [12,20,51], both of which were investigated by SECM. For the (BZ) oscillating reaction, a theoretical model involving a 11-reactions scheme allowed quantifying indirectly the concentration of reactive  $\text{BrO}_2^\bullet$  intermediates generated (down to  $7\ \mu\text{mol L}^{-1}$  in a  $2\ \mu\text{m}$  SECM gap) [21]. SECM could also demonstrate the ms lifetime of trialkylamine radical cations involved during anodic coreactant ECL [52]. These RIS are able to initiate new and strongly localized light emitting routes. They generate  $\mu\text{m}$  to  $\text{nm}$  localized ECL emission which can be imaged optically by footprinting the ECL RIS reactivity [53–55]. Besides amine coreactant oxidation, the oxalate oxidation process was quantitatively deciphered [12]. It required extremely small tip-substrate SECM gaps,  $d \approx 50\text{--}500\ \text{nm}$ , for the formation of the  $\text{C}_2\text{O}_4^{\bullet-}$  intermediate

with  $\tau=1.3 \mu\text{s}$  to be probed within gaps  $d < 73\text{nm}$ . Its later decomposition into  $\text{CO}_2^{\bullet-}$  was then revealed at longer distances,  $73\text{nm} < d < 500\text{nm}$  [12]. The detection of the latter RIS is promising for the investigation of  $\text{CO}_2$  reduction ( $\text{CO}_2\text{RR}$ ). The SECM could indeed trap  $\text{CO}_2^{\bullet-}$  formed during the  $\text{CO}_2\text{RR}$  within a sub-micro gap distance [11] allowing to determine its formal potential ( $E^0$ ), its heterogeneous formation rate constant ( $k^0$ ) and its dimerization rate ( $6.0 \times 10^8 \text{M}^{-1}\cdot\text{s}^{-1}$ ).



**Figure 2. a) Mechanistic scheme of  $\text{O}_2$  activation by iron porphyrin deciphered by SECM, and b) the LSV recorded at the SECM tip showing the collection of the reaction intermediates adapted from Ref. [10]. c) Reductive titration of MnV and MnIV to MnIII intermediates generated during transient pulse of OER (Figure 1e) and d) corresponding integrated charge density showing the different species detected and their apparent predominance potential zone adapted from Ref. [45].**

The SECM was also used to identify adsorbed RIS involved in the electrocatalytic oxygen evolution reaction (OER) using the SI-SECM mode [41–45]. Extensive studies of the reactive metal oxide RIS involved in OER electrocatalysis were proposed, such as cobalt [41,42], nickel/iron [43] or manganese [45] based catalysts. The different intermediates participating in the OER triggered by microelectrodes substrates coated with these catalysts were identified from the current transient associated to the conversion of redox titrant generated at the SECM tip (Figure 1e). It is illustrated in Figure 2c for the titration of Mn-oxide intermediates produced at different substrate potential. From the charge density extracted for each transient, the authors could draw nanoscale Pourbaix diagram showing the potential predominance and surface concentration in  $\text{Mn}^{\text{IV}}$  and  $\text{Mn}^{\text{V}}$  intermediates within electrochemically polarized amorphous  $\text{MnO}_x$  (Figure 2d).[45] Moreover, the quantitative analysis of the reaction rate between the catalysts intermediates and the water offered the possibility to determine the best environment needed to optimize the reactivity of the catalysts. The strategy is sound for benchmarking different OER electrocatalysts based on RIS identification. For example, the best OER kinetics with  $\text{Fe}^{\text{IV}}$  catalytic sites in  $\text{NiOOH}$  was obtained with a  $\text{Ni}_{0.82}\text{Fe}_{0.18}\text{OOH}$  structure. [43] Similarly,  $\text{Mn}^{\text{V}}$  sites were found to be more active in  $\text{CaMnO}_3$  Pervoskite than in amorphous  $\text{MnO}_x$  for which two different reactive  $\text{Mn}^{\text{V}}$  sites were proposed [45]. The strategy was extended to the identification of molecular RIS, such as surface-adsorbed ROS electrogenerated



during the OER at sp<sup>2</sup> carbon-containing BDD electrodes. the formation of at least two ROS was evidenced, one forming two orders of magnitude faster than the other but displaying a slower desorption rate [44]. If at that point the two populations of intermediates remain unknown, the role of pH and electrolyte on their surface concentration and reactivity was demonstrated. It opens interesting routes toward the study of other molecular RIS issued from other electrocatalytic reactions (ORR, HER, CO<sub>2</sub>RR..)

## Conclusions and outlooks

In this review, we demonstrated that confined environment in SECM configuration is a perfect condition to probe reactive intermediates involved in various (electro)chemical processes. The different methodologies of the SECM (Feedback, Generation/Collection, nanopipette, footprinting, and SI-SECM) already offered the possibility to probe numbers of reactive intermediates either generated on surfaces or in solution. The recent works have more particularly extended the limit of detection, enabling low concentrations and very low lifetimes (down to sub- $\mu$ s) ones. They also adapted to the description and understanding of more complex mechanisms involved in the electrocatalytic activation of small molecules through the ORR, OER and CO<sub>2</sub>RR or in ECL reactions. In the former case, detecting reaction intermediates is promising for the exploration of new mechanistic schemes, particularly in the field of molecular electrochemical activation of small molecules (O<sub>2</sub>, N<sub>2</sub>, NH<sub>3</sub>, CO<sub>2</sub>) [56]. In the latter case, it has enabled the definition of ECL imaging modes, by visualizing optically the footprint of the reaction of the RIS, with continuous improvement of the limit of detection [53,57,58]. Beyond SECM micro/nanotip, other electrochemical nanoprobe such as nanopipettes are actively developed, allowing the confinement of a chemical reaction in femtomolar volume. For instance, through the confinement of a meniscus droplet, scanning electrochemical cell microscopy was able to probe reactive intermediates by producing nanoscale footprints on surfaces [59]. It is a promising tool for analyzing surface intermediates in electrocatalysis or corrosion sciences [60,61]. Nanopipettes can also be used as nanosamplers [62,63] or used as nanopores [64,65]. The possibility to produce a bipolar electrode at the mouth of the pore [65], opens promising routes for the combined production and detection of very reactive species. Besides, efforts should be made to generalize RIS probing strategies or their benchmarking. To this end, micro/nanofabrication offers a solution for the mass production of nanoelectrochemical devices. Indeed, nanofabricated electrochemical ring-disk nanocavities are touching single enzyme electrochemical activity with further possibility of optical monitoring [64] whereas nanofluidic electrochemical devices have already shown their ability to explore the role of adsorption in single (bio)molecule electrochemistry [66,67].

## Funding sources

This work was financially supported by the ANR PIRaNa ANR-20-CE42-0001 project.

## References

- [1] S. Gligorovski, R. Strekowski, S. Barbat, D. Vione, Environmental Implications of Hydroxyl Radicals ( $\bullet$ OH), Chemical Reviews. 115 (2015) 13051–13092.

<https://doi.org/10.1021/cr500310b>.

- [2] X. Huang, J.T. Groves, Oxygen Activation and Radical Transformations in Heme Proteins and Metalloporphyrins, *Chemical Reviews*. 118 (2018) 2491–2553. <https://doi.org/10.1021/acs.chemrev.7b00373>.
- [3] K. Hu, Y.L. Liu, A. Oleinick, M. V. Mirkin, W.H. Huang, C. Amatore, Nanoelectrodes for intracellular measurements of reactive oxygen and nitrogen species in single living cells, *Current Opinion in Electrochemistry*. 22 (2020) 44–50. <https://doi.org/10.1016/j.coelec.2020.04.003>.
- [4] J.G. Roberts, M.A. Voinov, A.C. Schmidt, T.I. Smirnova, L.A. Sombers, The Hydroxyl Radical is a Critical Intermediate in the Voltammetric Detection of Hydrogen Peroxide, *Journal of the American Chemical Society*. 138 (2016) 2516–2519. <https://doi.org/10.1021/jacs.5b13376>.
- [5] S. den Hartog, M. Samanipour, H.Y.V. Ching, S. Van Doorslaer, T. Breugelmans, A. Hubin, J. Ustarroz, Reactive oxygen species formation at Pt nanoparticles revisited by electron paramagnetic resonance and electrochemical analysis, *Electrochemistry Communications*. 122 (2021) 106878. <https://doi.org/10.1016/j.elecom.2020.106878>.
- [6] Z. Xu, Z. Liang, W. Guo, R. Zou, In situ/operando vibrational spectroscopy for the investigation of advanced nanostructured electrocatalysts, *Coordination Chemistry Reviews*. 436 (2021) 213824. <https://doi.org/10.1016/j.ccr.2021.213824>.
- [7] J.C. Dong, M. Su, V. Briega-Martos, L. Li, J.B. Le, P. Radjenovic, X.S. Zhou, J.M. Feliu, Z.Q. Tian, J.F. Li, Direct in Situ Raman Spectroscopic Evidence of Oxygen Reduction Reaction Intermediates at High-Index Pt(hkl) Surfaces, *Journal of the American Chemical Society*. 142 (2020) 715–719. <https://doi.org/10.1021/jacs.9b12803>.
- [8] X.S. Zhou, B.W. Mao, C. Amatore, R.G. Compton, J.L. Marignier, M. Mostafavi, J.F. Nierengarten, E. Maisonhaute, Transient electrochemistry: Beyond simply temporal resolution, *Chemical Communications*. 52 (2016) 251–263. <https://doi.org/10.1039/c5cc07953e>.
- [9] B.R. Horrocks, *Scanning Electrochemical Microscopy*, (n.d.) 444–490.
- [10]\*\*J.M. Noel, N. Kostopoulos, C. Achaibou, C. Fave, E. Anxolabéhère-Mallart, F. Kanoufi, Probing the Activity of Iron Peroxo Porphyrin Intermediates in the Reaction Layer during the Electrochemical Reductive Activation of O<sub>2</sub>, *Angewandte Chemie - International Edition*. 59 (2020) 16376–16380. <https://doi.org/10.1002/anie.202004977>.

**Detection of Iron Peroxo Porphyrin Intermediates in the course of the oxygen electro-reductive activation by iron porphyrin, quantitative description of the whole catalytic process and establishment of a porphyrin structure-electrocatalytic efficiency relationship.**

- [11]\* T. Kai, M. Zhou, Z. Duan, G.A. Henkelman, A.J. Bard, Detection of CO<sub>2</sub>•<sup>-</sup> in the Electrochemical Reduction of Carbon Dioxide in N,N-Dimethylformamide by Scanning Electrochemical Microscopy, *Journal of the American Chemical Society*. 139 (2017) 18552–18557. <https://doi.org/10.1021/jacs.7b08702>.

**Direct probing of short lifetime  $\text{CO}_2^{\bullet-}$  produced during  $\text{CO}_2$  reduction in a submicrometer gap between two ultramicroelectrodes.**

- [12]\*\*T. Kai, M. Zhou, S. Johnson, H.S. Ahn, A.J. Bard, Direct Observation of  $\text{C}_2\text{O}_4^{\bullet-}$  and  $\text{CO}_2^{\bullet-}$  by Oxidation of Oxalate within Nanogap of Scanning Electrochemical Microscope, *Journal of the American Chemical Society*. 140 (2018) 16178–16183. <https://doi.org/10.1021/jacs.8b08900>.

**Selective detection of  $\text{C}_2\text{O}_4^{\bullet-}$  and  $\text{CO}_2^{\bullet-}$  generated during the oxidation of oxalate by varying the gap between a nanoelectrode and an ultramicroelectrode from the submicrometer to the nanometer scale.**

- [13] T. Sun, D. Wang, M. V. Mirkin, Tunneling Mode of Scanning Electrochemical Microscopy: Probing Electrochemical Processes at Single Nanoparticles, *Angewandte Chemie - International Edition*. 57 (2018) 7463–7467. <https://doi.org/10.1002/anie.201801115>.
- [14] T. Bo, X. Wang, R. Jia, L. Han, H.L. Xin, H. Zhang, E.M. Miller, M. V. Mirkin, Probing Activities of Individual Catalytic Nanoflakes by Tunneling Mode of Scanning Electrochemical Microscopy, *Journal of Physical Chemistry C*. 125 (2021) 25525–25532. <https://doi.org/10.1021/acs.jpcc.1c07309>.
- [15] A. Oleinick, Y. Yu, M. V. Mirkin, I. Svir, C. Amatore, Theory and Simulations for the Electron Transfer/Ion Transfer Mode of SECM with Electroactive Species Present in Both Liquid Phases, *ChemElectroChem*. 6 (2019) 189–194. <https://doi.org/10.1002/celc.201800793>.
- [16]\*\*M. Zhou, Y. Yu, K. Hu, M. V. Mirkin, Nanoelectrochemical Approach To Detecting Short-Lived Intermediates of Electrocatalytic Oxygen Reduction, *Journal of the American Chemical Society*. 137 (2015) 6517–6523. <https://doi.org/10.1021/ja512482n>.

**Probing of very short lifetime superoxide radical during the ORR in neutral pH by reaching a 1 nm gap distance between a nanopipette and the substrate.**

- [17] A. Oleinick, Y. Yu, I. Svir, M. V. Mirkin, C. Amatore, Theory and Simulations for the Electron-Transfer/Ion-Transfer Mode of Scanning Electrochemical Microscopy in the Presence or Absence of Homogenous Kinetics, *ChemElectroChem*. 4 (2017) 287–295. <https://doi.org/10.1002/celc.201600583>.
- [18] A. Oleinick, Y. Yu, I. Svir, M. V. Mirkin, C. Amatore, Theory and Simulations for the Electron-Transfer/Ion-Transfer Mode of Scanning Electrochemical Microscopy in the Presence or Absence of Homogenous Kinetics, *ChemElectroChem*. 4 (2017) 287–295. <https://doi.org/10.1002/celc.201600583>.
- [19] P.R. Unwin, J. V Macpherson, R.D. Martin, C.F. McConville, Scanning Electrochemical Microscopy as a Dynamic Probe of Metal Adsorption, Nucleation and Growth on Surfaces : Silver Deposition, In *International Symposium on Localized In Situ Methods for Investigating Electrochemical Interfaces*, Ed. S. R. Taylor, A. C. Hillier and M. Seo,

Honolulu, Hi. 99 (1999) 104–121.

- [20] F. Kanoufi, A.J. Bard, Electrogenerated Chemiluminescence. 65. An Investigation of the Oxidation of Oxalate by Tris(polypyridine) Ruthenium Complexes and the Effect of the Electrochemical Steps on the Emission Intensity, *The Journal of Physical Chemistry B*. 103 (1999) 10469–10480. <https://doi.org/10.1021/jp992368s>.
- [21] T.J. Stockmann, J.-M. Noël, S. Ristori, C. Combellas, A. Abou-Hassan, F. Rossi, F. Kanoufi, Scanning Electrochemical Microscopy of Belousov–Zhabotinsky Reaction: How Confined Oscillations Reveal Short Lived Radicals and Auto-Catalytic Species, *Analytical Chemistry*. 87 (2015) 9621–9630. <https://doi.org/10.1021/acs.analchem.5b01238>.
- [22] M.A. Bhat, N. Nioradze, J. Kim, S. Amemiya, A.J. Bard, In Situ Detection of the Adsorbed Fe(II) Intermediate and the Mechanism of Magnetite Electrodeposition by Scanning Electrochemical Microscopy, *Journal of the American Chemical Society*. 139 (2017) 15891–15899. <https://doi.org/10.1021/jacs.7b08835>.
- [23] A. Atesyan, O. Belhadj, C. Combellas, F. Kanoufi, V. Rouchon, J.M. Noël, Scanning Electrochemical Microscopy for the Electroless Deposition of Gold on Natural Pyrite: Effect of Ferric Ions, *ChemElectroChem*. (2019). <https://doi.org/10.1002/celc.201801271>.
- [24]\*\*K. Barman, X. Wang, R. Jia, G. Askarova, G. Hu, M. V. Mirkin, Voltage-Driven Molecular Catalysis of Electrochemical Reactions, *Journal of the American Chemical Society*. 143 (2021) 17344–17347. <https://doi.org/10.1021/jacs.1c07934>.

**Immobilization of a redox film on a nanoelectrode to probe indirectly H<sub>2</sub>O<sub>2</sub> electrogenerated or electro-regenerated at individual nanoparticles.**

- [25] K. Barman, X. Wang, R. Jia, M. V. Mirkin, Mediated Charge Transfer at Nanoelectrodes: A New Approach to Electrochemical Reactivity Mapping and Nanosensing, *Journal of the American Chemical Society*. 143 (2021) 8547–8551. <https://doi.org/10.1021/jacs.1c02532>.
- [26] A.I.B. Romo, D.S. Abreu, T. de F. Paulo, M.S.P. Carepo, E.H.S. Sousa, L. Lemus, C. Aliaga, A.A. Batista, O.R. Nascimento, H.D. Abruña, I.C.N. Diógenes, Hydroxyl Radical Generation and DNA Nuclease Activity: A Mechanistic Study Based on a Surface-Immobilized Copper Thioether Clip-Phen Derivative, *Chemistry - A European Journal*. 22 (2016) 10081–10089. <https://doi.org/10.1002/chem.201601719>.
- [27] A. Latus, J.-M. Noël, E. Volanschi, C. Lagrost, P. Hapiot, Scanning Electrochemical Microscopy Studies of Glutathione-Modified Surfaces . An Erasable and Sensitive-to-Reactive Oxygen Species Surface, *Langmuir*. 27 (2011) 11206–11211. <https://doi.org/dx.doi.org/10.1021/la2020034>.
- [28] J.-M. Noël, A. Latus, C. Lagrost, E. Volanschi, P. Hapiot, Evidence for OH radical production during electrocatalysis of oxygen reduction on pt surfaces: Consequences and application, *Journal of the American Chemical Society*. 134 (2012) 2835–2841. <https://doi.org/10.1021/ja211663t>.

- [29] H. Shiku, I. Uchida, T. Matsue, Microfabrication of alkylsilanized glass substrate by electrogenerated hydroxyl radical using scanning electrochemical microscopy, *Langmuir*. 13 (1997) 7239–7244. <https://doi.org/10.1021/la970554o>.
- [30] H. Hazimeh, S. Nunige, R. Cornut, C. Lefrou, C. Combellas, F. Kanoufi, Surface reactivity from electrochemical lithography: Illustration in the steady-state reductive etching of perfluorinated surfaces, *Analytical Chemistry*. 83 (2011). <https://doi.org/10.1021/ac201255c>.
- [31]\* S. Nunige, R. Cornut, H. Hazimeh, F. Hauquier, C. Lefrou, C. Combellas, F. Kanoufi, Reactivity of surfaces determined by local electrochemical triggering: A bromo-terminated self-assembled monolayer, *Angewandte Chemie - International Edition*. 51 (2012). <https://doi.org/10.1002/anie.201201083>.

**Quantification of Br<sub>2</sub> reactivity with a self assembled monolayer and with a scavenger using the footprinting methodology.**

- [32] B. Vaske, M. Schaub, F. Meiners, J.H. Ross, J. Christoffers, G. Wittstock, Modification and Patterning of Self-Assembled Monolayers Using Electrogenerated Etchants and Homogeneous Scavenging Reactions in a Scanning Electrochemical Microscope, *ChemElectroChem*. 8 (2021) 3192–3202. <https://doi.org/10.1002/celc.202100718>.
- [33] J.M. Noël, J. Médard, C. Combellas, F. Kanoufi, Prussian Blue Degradation during Hydrogen Peroxide Reduction: A Scanning Electrochemical Microscopy Study on the Role of the Hydroxide Ion and Hydroxyl Radical, *ChemElectroChem*. 3 (2016) 1178–1184. <https://doi.org/10.1002/celc.201600196>.
- [34]\* D. Zhan, L. Han, J. Zhang, K. Shi, J.Z. Zhou, Z.W. Tian, Z.Q. Tian, Confined Chemical Etching for Electrochemical Machining with Nanoscale Accuracy, *Accounts of Chemical Research*. 49 (2016) 2596–2604. <https://doi.org/10.1021/acs.accounts.6b00336>.

**confined etchant layer technique for surfaces microfabrication with nanometer scale accuracy.**

- [35] L. Han, Z. Hu, M.M. Sartin, X. Wang, X. Zhao, Y. Cao, Y. Yan, D. Zhan, Z.Q. Tian, Direct Nanomachining on Semiconductor Wafer By Scanning Electrochemical Microscopy, *Angewandte Chemie - International Edition*. 59 (2020) 21129–21134. <https://doi.org/10.1002/anie.202008697>.
- [36] L. Han, Y. Wang, M.M. Sartin, D. Zhan, Z.Q. Tian, Chemical Etching Processes at the Dynamic GaAs/Electrolyte Interface in the Electrochemical Direct-Writing Micromachining, *ACS Applied Electronic Materials*. 3 (2021) 437–444. <https://doi.org/10.1021/acsaelm.0c00979>.
- [37] D. Zigah, J. Rodríguez-López, A.J. Bard, Quantification of photoelectrogenerated hydroxyl radical on TiO<sub>2</sub> by surface interrogation scanning electrochemical microscopy, *Physical Chemistry Chemical Physics*. 14 (2012) 12764–12772. <https://doi.org/10.1039/c2cp40907k>.
- [38] H.S. Park, K.C. Leonard, A.J. Bard, Surface Interrogation Scanning Electrochemical

- Microscopy (SI-SECM) of Photoelectrochemistry at a W/Mo-BiVO<sub>4</sub> Semiconductor Electrode: Quantification of Hydroxyl Radicals during Water Oxidation, *The Journal of Physical Chemistry C*. 117 (2013) 12093–12102. <https://doi.org/10.1021/jp400478z>.
- [39] B.H. Simpson, J. Rodríguez-López, Electrochemical Imaging and Redox Interrogation of Surface Defects on Operating SrTiO<sub>3</sub> Photoelectrodes, *Journal of the American Chemical Society*. 137 (2015) 14865–14868. <https://doi.org/10.1021/jacs.5b10256>.
- [40] M.R. Krumov, B.H. Simpson, M.J. Counihan, J. Rodríguez-López, In Situ Quantification of Surface Intermediates and Correlation to Discharge Products on Hematite Photoanodes Using a Combined Scanning Electrochemical Microscopy Approach, *Analytical Chemistry*. 90 (2018) 3050–3057. <https://doi.org/10.1021/acs.analchem.7b04896>.
- [41] H.S. Ahn, A.J. Bard, Surface interrogation of CoPi water oxidation catalyst by scanning electrochemical microscopy, *Journal of the American Chemical Society*. 137 (2015) 612–615. <https://doi.org/10.1021/ja511740h>.
- [42] H.S. Ahn, A.J. Bard, Switching Transient Generation in Surface Interrogation Scanning Electrochemical Microscopy and Time-of-Flight Techniques, *Analytical Chemistry*. 87 (2015) 12276–12280. <https://doi.org/10.1021/acs.analchem.5b03542>.
- [43] H.S. Ahn, A.J. Bard, Surface Interrogation Scanning Electrochemical Microscopy of Ni<sub>1-x</sub>FexOOH (0 < x < 0.27) Oxygen Evolving Catalyst: Kinetics of the “fast” Iron Sites, *Journal of the American Chemical Society*. 138 (2016) 313–318. <https://doi.org/10.1021/jacs.5b10977>.
- [44]\*\* M.J. Counihan, W. Setwipatanachai, J. Rodríguez-López, Interrogating the Surface Intermediates and Water Oxidation Products of Boron-Doped Diamond Electrodes with Scanning Electrochemical Microscopy, *ChemElectroChem*. 6 (2019) 3507–3515. <https://doi.org/10.1002/celec.201900659>.

**First example of the detection of reactive oxygen species adsorbed at the surface of an electrode during the oxygen evolution reaction.**

- [45]\* Z. Jin, A.J. Bard, Surface Interrogation of Electrodeposited MnO<sub>x</sub> and CaMnO<sub>3</sub> Perovskites by Scanning Electrochemical Microscopy: Probing Active Sites and Kinetics for the Oxygen Evolution Reaction, *Angewandte Chemie - International Edition*. 60 (2021) 794–799. <https://doi.org/10.1002/anie.202008052>.

**Identification of the reactive Mn adsorbed intermediates species and quantification of their reactivity during the oxygen evolution reaction.**

- [46] H.S. Park, K.C. Leonard, A.J. Bard, Surface Interrogation Scanning Electrochemical Microscopy (SI-SECM) of Photoelectrochemistry at a W/Mo-BiVO<sub>4</sub> Semiconductor Electrode: Quantification of Hydroxyl Radicals during Water Oxidation, *The Journal of Physical Chemistry C*. 117 (2013) 12093–12102. <https://doi.org/10.1021/jp400478z>.
- [47] S. den Hartog, M. Samanipour, H.Y.V. Ching, S. Van Doorslaer, T. Breugelmans, A. Hubin, J. Ustarroz, Reactive oxygen species formation at Pt nanoparticles revisited by electron paramagnetic resonance and electrochemical analysis, *Electrochemistry*

- Communications. 122 (2021) 106878. <https://doi.org/10.1016/j.elecom.2020.106878>.
- [48] S.J. Percival, J.E. Dick, A.J. Bard, Cathodically Dissolved Platinum Resulting from the O<sub>2</sub> and H<sub>2</sub>O<sub>2</sub> Reduction Reactions on Platinum Ultramicroelectrodes, *Analytical Chemistry*. 89 (2017) 3087–3092. <https://doi.org/10.1021/acs.analchem.6b04832>.
- [49] J.-M. Noël, Y. Yu, M. V Mirkin, Dissolution of Pt at Moderately Negative Potentials during Oxygen Reduction in Water and Organic Media, *Langmuir*. 29 (2013) 1346–1350. <https://doi.org/dx.doi.org/10.1021/la304694d>.
- [50] M.L. Pegis, B.A. McKeown, N. Kumar, K. Lang, D.J. Wasylenko, X.P. Zhang, S. Raagei, J.M. Mayer, Homogenous electrocatalytic oxygen reduction rates correlate with reaction overpotential in acidic organic solutions, *ACS Central Science*. 2 (2016) 850–856. <https://doi.org/10.1021/acscentsci.6b00261>.
- [51] W. Miao, J.-P. Choi, A.J. Bard, Electrogenenerated Chemiluminescence 69: The Tris(2,2'-bipyridine)ruthenium(II), (Ru(bpy)<sub>3</sub><sup>2+</sup>)/Tri- n -propylamine (TPrA) System RevisitedA New Route Involving TPrA •+ Cation Radicals, *Journal of the American Chemical Society*. 124 (2002) 14478–14485. <https://doi.org/10.1021/ja027532v>.
- [52] W. Miao, J.-P. Choi, A.J. Bard, Electrogenenerated Chemiluminescence 69: The Tris(2,2'-bipyridine)ruthenium(II), (Ru(bpy)<sub>3</sub><sup>2+</sup>)/Tri- n -propylamine (TPrA) System RevisitedA New Route Involving TPrA •+ Cation Radicals, *Journal of the American Chemical Society*. 124 (2002) 14478–14485. <https://doi.org/10.1021/ja027532v>.
- [53] M. Sentic, M. Milutinovic, F. Kanoufi, D. Manojlovic, S. Arbault, N. Sojic, Mapping electrogenerated chemiluminescence reactivity in space: Mechanistic insight into model systems used in immunoassays, *Chemical Science*. 5 (2014). <https://doi.org/10.1039/c4sc00312h>.
- [54] A. Fiorani, D. Han, D. Jiang, D. Fang, F. Paolucci, N. Sojic, G. Valenti, Spatially resolved electrochemiluminescence through a chemical lens, *Chemical Science*. (2020). <https://doi.org/10.1039/D0SC04210B>.
- [55] A. Zanut, A. Fiorani, S. Canola, T. Saito, N. Ziebart, S. Rapino, S. Rebecani, A. Barbon, T. Irie, H.-P. Josel, F. Negri, M. Marcaccio, M. Windfuhr, K. Imai, G. Valenti, F. Paolucci, Insights into the mechanism of coreactant electrochemiluminescence facilitating enhanced bioanalytical performance, *Nature Communications*. 11 (2020) 2668. <https://doi.org/10.1038/s41467-020-16476-2>.
- [56] L. Merakeb, M. Robert, Advances in molecular electrochemical activation of dinitrogen, *Current Opinion in Electrochemistry*. 29 (2021) 100834. <https://doi.org/10.1016/j.coelec.2021.100834>.
- [57] J. Zhang, S. Arbault, N. Sojic, D. Jiang, Electrochemiluminescence Imaging for Bioanalysis, *Annual Review of Analytical Chemistry*. 12 (2019) 275–295. <https://doi.org/10.1146/annurev-anchem-061318-115226>.
- [58] J. Dong, Y. Lu, Y. Xu, F. Chen, J. Yang, Y. Chen, J. Feng, Direct imaging of single-molecule electrochemical reactions in solution, *Nature*. 596 (2021) 244–249. <https://doi.org/10.1038/s41586-021-03715-9>.

- [59] P.M. Kirkman, A.G. Güell, A.S. Cuharuc, P.R. Unwin, Spatial and Temporal Control of the Diazonium Modification of sp<sup>2</sup> Carbon Surfaces, *Journal of the American Chemical Society*. 136 (2014) 36–39. <https://doi.org/10.1021/ja410467e>.
- [60] E. Daviddi, V. Shkirskiy, P.M. Kirkman, M.P. Robin, C.L. Bentley, P.R. Unwin, Nanoscale electrochemistry in a copper/aqueous/oil three-phase system: surface structure–activity-corrosion potential relationships, *Chemical Science*. 12 (2021) 3055–3069. <https://doi.org/10.1039/D0SC06516A>.
- [61] C.L. Bentley, M. Kang, P.R. Unwin, Nanoscale Surface Structure–Activity in Electrochemistry and Electrocatalysis, *Journal of the American Chemical Society*. 141 (2019) 2179–2193. <https://doi.org/10.1021/jacs.8b09828>.
- [62] Y. Wang, R. Pan, D. Jiang, D. Jiang, H.Y. Chen, Nanopipettes for the Electrochemical Study of Enhanced Enzymatic Activity in a Femtoliter Space, *Analytical Chemistry*. 93 (2021) 14521–14526. <https://doi.org/10.1021/acs.analchem.1c03341>.
- [63] A.G. Ewing, K. Hu, R. Jia, A. Hatamie, K.L. Le Vo, M. V. Mirkin, Correlating molecule count and release kinetics with vesicular size using open carbon nanopipettes, *Journal of the American Chemical Society*. 142 (2020) 16910–16914. <https://doi.org/10.1021/jacs.0c07169>.
- [64] K. Fu, S.R. Kwon, D. Han, P.W. Bohn, Single Entity Electrochemistry in Nanopore Electrode Arrays: Ion Transport Meets Electron Transfer in Confined Geometries, *Accounts of Chemical Research*. 53 (2020) 719–728. <https://doi.org/10.1021/acs.accounts.9b00543>.
- [65] Y.L. Ying, Y.X. Hu, R. Gao, R.J. Yu, Z. Gu, L.P. Lee, Y.T. Long, Asymmetric Nanopore Electrode-Based Amplification for Electron Transfer Imaging in Live Cells, *Journal of the American Chemical Society*. 140 (2018) 5385–5392. <https://doi.org/10.1021/jacs.7b12106>.
- [66] E. Kätelhön, K.J. Krause, K. Mathwig, S.G. Lemay, B. Wolfrum, Noise Phenomena Caused by Reversible Adsorption in Nanoscale Electrochemical Devices, *ACS Nano*. 8 (2014) 4924–4930. <https://doi.org/10.1021/nn500941g>.
- [67] L. Rassaei, K. Mathwig, S. Kang, H.A. Heering, S.G. Lemay, Integrated Biodetection in a Nanofluidic Device, *ACS Nano*. 8 (2014) 8278–8284. <https://doi.org/10.1021/nn502678t>.