Journal of Solid State Electrochemistry (2023) 27:1747–1754
https://doi.org/10.1007/s10008-023-05410-3

ORIGINAL PAPER

Past and present of electrochemical science in Hungary

Tamás Pajkossy[1]

Received: 17 January 2023 / Revised: 22 January 2023 / Accepted: 24 January 2023 / Published online: 8 February 2023

Abstract
The electrochemistry-related scientific activities in Hungary over the past 3 decades are reviewed. In the first section, we summarize those research areas that are already ceased; in the next section, the ongoing research is discussed; finally, the trends and outlook are highlighted. A special emphasis is put on new experimental methods elaborated in the country.

Introduction

The history of Hungarian electrochemistry along with its background can perhaps be best shown through the life and activities of the outstanding electrochemist-scientists, just as was recently done by György Inzelt [1]. Out of the many outstanding scientists listed therein, two of them, Tibor Erdey-Grúz (1902–1976) [1], [2, page 352] and Ernő Pungor (1923–2007) [1], [2, page 770] [3], were active in the twentieth century, established two major directions of electrochemistry in Hungary. Their schools: students, followers, and "scientific descendants"—and the ideas they introduced and represented are still noteworthy. One of these directions was electrode kinetics, studied mainly by the school of Erdey-Grúz; the other is certain aspects of electroanalytical chemistry, pursued by people of the school of Pungor.

A previous snapshot of the state of Hungarian electrochemistry can be read in an invitation letter [4] to the 47th International Society of Electrochemistry meeting, held in Veszprém and Balatonfüred, Hungary, in 1996. This letter has been written by the principal local organizer, György Inzelt, now the doyen of the Hungarian electrochemists. It comprises a two-page-long overview of the electrochemical science in Hungary up to the date of the conference.

The present article reviews activities since 1996, starting where [4] has been finished. Since 1996, many of the scientists mentioned in [4] have finished related activities and have retired or are deceased; these activities are summarized in the "Finished activities" section; the present, ongoing activities are reviewed in the "Ongoing activities" section. Finally, the trends and future prospects are listed in the "Summary and outlook" section.

Finished activities

Important electrochemical studies and laboratories were at research institutes[1] of the Hungarian Academy of Sciences.

Probably the most efficient and best-known electrochemist of the early years of the twenty-first century was György Horányi (†2006) [1], [2, page 461]. He performed radiotracer experiments to clarify details of adsorption (electrosorption) and electrocatalytic phenomena at electrode surfaces and of ion-exchange processes in polymer-modified electrodes. In particular, important are his studies on sulfate adsorption on many diverse metals and oxide surfaces [5].

Erika Kálmán (†2009) with her group studied the electrochemical corrosion of metals with a focus on corrosion inhibition phenomena, e.g., of phosphonates on steel in neutral aqueous electrolytes, in the context of the structure of the surface layer [6]. The effect of self-assembling on corrosion protection as well as the kinetics of self-assembling have been characterized in [7] and [8], respectively. An analysis of the role of biofilms in corrosion processes is also noteworthy [9]. People of this group recently participated in a long project characterizing carbon nanotube arrays in electrochemical capacitors [10].

Underpotential deposition of metals and fundamental aspects of metal corrosion kinetics have been studied by Sándor Szabó (†2018) [11, 12]. Besides the investigation of electrochemical noise [13], corrosion protection properties

✉ Tamás Pajkossy
pajkossy.tamas@ttk.mta.hu

[1] Institute of Materials and Environmental Chemistry, Research Centre for Natural Sciences, Budapest, Hungary

---

[1] At present, all these institutes belong to the Research Centre of Natural Sciences of the Eötvös Loránd Research Network.

of various inhibitors [14], and organic coatings [15] were characterized, electrochemical aspects of electrocoagulation have been analyzed [16] by the group of Béla Lengyel.

For understanding relaxation processes within the electrochemical double layer, impedance studies have been performed on noble metals in aqueous solutions and in ionic liquids by Tamás Pajkossy [17].

There have been a number of groups at major Hungarian universities whose electrochemistry-related activities were significant. They are as follows:

Following the long-term traditions in the Department of Analytical Chemistry at the Technical University Budapest,[2] headed for a long time by Ernő Pungor, the group of Klára Tóth (†2013) worked on the theory and utilization of ion-selective electrodes, in particular of ones with bis-crown ether, calixarene, etc., derivatives in polymer membranes. These are selective to K^+, Na^+, Pb^{2+}, H^+, and Zn^{2+} ions. Extensive efforts were made to characterize various physicochemical properties of these membranes; characteristic publications are [18–20]. The members of the group made significant contributions to flow analytical methods [21]. Some of the sensor and method developments were supported by the electrochemical instrumentation company, Radelkis (managed by Jenő Havas) and reached industrial production [22].

György Farsang (†2009), professor of analytical chemistry at the Eötvös Loránd University, Budapest, studied anodic reactions (electrochemical oxidation and dimerization) of various halogenated aniline compounds in organic solutions using microelectrodes and high scan rate cyclic voltammetry [23].

Pál Joó (†2022), professor of colloid chemistry at the University of Debrecen up till his retirement in 2007, studied mostly adsorption onto and transport processes through colloidal systems by electrochemical and radiochemical methods [24].

Nonlinear dynamics of oscillatory and chaotic metal electrodissolution were studied both experimentally and theoretically by Vilmos Gáspár and István Z. Kiss at the University of Debrecen [25, 26]. Nonequilibrium phase diagrams were constructed, and their dependence on various experimental parameters, such as mass transport conditions and solution resistance, etc., were determined. Control and synchronization algorithms, including neural networks, were developed for the chaotic dynamics of single and multielectrode systems.

Kálmán Varga (†2009) at the University of Veszprém[3] has studied corrosion and radioactive contamination processes on metal surfaces typical in primary circuits of nuclear power plants [27]. Apart from these, other combined radiochemical and electrochemical electrosorption experiments have been performed with noble metal surfaces like the one in [28].

Csaba Visy at the University of Szeged has studied electrically conductive polymers, charge transport, and structural transformations therein using in situ combined spectroelectrochemical methods since the late 1980s [29, 30]; since the millennium, the main research direction has been the production, characterization, and application possibilities of composite materials based on conducting polymers [31]. Such composites with special magnetic, photocatalytic, thermoelectric, and biocatalytic properties have been successfully produced; a characteristic example is in [32].

László Dobos (†2008), electrical engineer at the University of Szeged, manufactured a number of potentiostats for Hungarian universities and research institutions, according to their specific needs. In the 1990s, his affordable computer-controlled potentiostats were practically on the same technical level as the commercial potentiostats made in Western countries.

Ongoing activities

Electrode kinetics

Following many decades of “Erdey-Grúz tradition” in the physical chemistry department of the Eötvös Loránd University, Budapest, most of the research activities are related to electrode kinetics. At present, there are three main research directions in that department, mostly associated with three senior electrochemists:

György Inzelt has been studying the deposition, properties, and transformations of various electroactive layers (conducting polymers, various metal phthalocyanines, lead sulfate, etc.) on inert electrodes within an electrochemical quartz crystal microbalance (EQCM). Important summarizing publications on conducting polymers are [33] and [34].

Győző G. Láng and coworkers have been studying polymer film electrodes, mostly poly(3,4-ethylenedioxythiophene) (PEDOT), in particular, it is aging as well as overoxidation and its consequences [35]. From an environmental protection point of view important are their studies on perchlorate reduction on various metals [36].

Soma Vesztergom constructed a mathematical model of hydrogen evolution from a mildly acidic, unbuffered, stirred aqueous solution when the hydrogen gas stems both from H^+ ions and from water. This model’s predictions are in accord with hydrogen evolution experiments carried out with RDE [37], also even if hydrogen evolution proceeds parallel to a metal deposition [38].

---

[2] At present, the name of TU Budapest is Budapest University of Technology and Economics.

[3] At present, its name is University of Pannonia.

The research activities of Janáky and his group at the University of Szeged have been focusing on semiconductor photoelectrochemistry. New photoelectrode assemblies were designed for energetics-related processes (e.g., water oxidation and CO_2 reduction) [39, 40], or to drive value-adding processes yielding chemicals or fuels. A new instrument—an in situ ultrafast spectroelectrochemical tool—was constructed for tracking light-induced processes at the fs-ps timescale under electrochemical control [41] and was used for the study of optically active perovskites.

Tamás Pajkossy has recently reconsidered the theories of electrode charge transfer in cases of diffusional and coverage hindrances, for conditions of both voltammetry and impedance spectroscopy. His theories yield simple, exact equations [42].

Theories of double-layer structure play a big role in understanding electrode kinetics. Dezső Boda and coworkers at the University of Veszprém[3] have been doing Monte Carlo simulations for the properties of various structures having electrochemical relevance: electrical double layers [43], ion channels [44], and ion atmospheres [45]. In their models, the ions of the electrolyte are charged hard spheres distributed in an implicit continuum solvent. With this—apparently simple—modeling even complex phenomena can be explained, provided that the important degrees of freedom are included in the model [46].

Electroanalysis

The development of chemical sensors and biosensors based on electrochemical transducers and "nanoelectrochemistry" is the main research interest of Róbert Gyurcsányi's group at the TU Budapest[2]. Novel sensing concepts, materials, and investigation methods have been introduced to support the application of ion sensors for ultra-trace analysis, bioanalysis, and field deployment. Perhaps the most important innovation was the development of the selective solid-state ion channels based on chemically modified nanopores [47], which also enabled the use of hydrophilic complexing agents of biological origin for the potentiometric measurement of ions and polyions [48]. Through novel nanoscale electrochemical sensing and synthetic concepts, they made possible the detection of single entities/particles such as viruses [49] as well as the generation of affinity ligands for selective protein recognition based on surface-imprinted electropolymerized nanofilms [50].

The group of Géza Nagy at the University of Pécs contributed to the advancement of scanning electrochemical microscopy by employing multi-barrel measuring tips containing ion-selective microelectrodes [51] in potentiostatic mode to studies related to corrosion and life sciences. They have been also elaborating and using various amperometric and potentiometric methods for many and diverse analytical purposes; a characteristic example is concentration determination in tortuous media [52].

Applied electrochemistry

The fundamental research on electrode kinetics made at Eötvös Loránd University had also practical outcomes. The development of hydrogen-based fuel cells and their application were also a field of activity of György Inzelt's group [53]. Győző G. Láng and coworkers elaborated a procedure for the electrochemical generation of ferrate salts [54, 55], which can eliminate even the chlorinated organic compounds, e.g., from polluted groundwater.

The staff of the electrochemistry laboratory of the Institute of Solid State Physics[4] in Budapest has long been dealing with various aspects of electrodeposition of metals. Imre Bakonyi initiated the studies of the electrodeposition of nanocrystalline metals in the early 1990s [56] as well as that of ferromagnetic/nonmagnetic multilayers exhibiting giant magnetoresistance. The latter was elaborated with László Péter, leading to an important review of the topic [57]. László Péter continued the metal electroplating studies with composition depth profile analysis of electrodeposited alloys and multilayers [58], and fine structural studies of various metals and alloys [59].

A group of the KFKI Atomic Energy Research Institute[5] in Budapest has been studying corrosion-related problems appearing in primary circuits of the pressurized water nuclear power plants. Their representative publication is [60], and remarkable technical details are in [61].

Magda Lakatos-Varsányi (Bay Institute, Budapest) made various metal layers by pulse plating (e.g., [62]) and characterized metals from the corrosion point of view (e.g., [63]).

The Corrosion Research Group of the University of Veszprém[3] has been focusing its activities on industrial corrosion prevention. The group regularly performs industrial corrosion root-cause analyses. Recent academic research includes corrosion testing of structural materials of the oil industry [64] and improvements in evaluation methods for corrosion-related electrochemical techniques [65].

Balázs Endrődi and Csaba Janáky, with their group at the University of Szeged, perform studies of industrial electrochemical processes, mainly water splitting and CO_2 reduction, under industrially relevant conditions. New electrolyzer cell and stack architectures [66], membrane electrode assemblies, and operational protocols [67] have been developed.

---

[4] At present, it is a part of the Wigner Research Centre of the Eötvös Loránd Research Network.

[5] At present, it is a part of the Centre for Energy Research of the Eötvös Loránd Research Network.

Development of catalysts for the PEM fuel cell anodes is done at the Institute of Materials and Environmental Chemistry[1], Budapest, in the group of András Tompos. As it can be demonstrated, the Pt catalyst becomes more stable and CO tolerant if the support is a mixed Ti–W oxide [68] or Ti-Mo oxide [69] on activated carbon rather than the usual pure activated carbon.

A form of local corrosion in electronic circuits is caused by electromigration leading to dendritic shortcuts between metal stripes, which finally result in the failure of the circuit. Electromigration phenomena are studied at the Department of Electronic Technology of the TU Budapest[2] [70].

Instrument development

In general, in most laboratories, factory-built instruments are used. Nevertheless, a couple of special devices/setups have been assembled—or are under development. These are as follows:

A special setup for controlling an RRDE has been assembled by Soma Vesztergom. The potential of the two working electrodes can be controlled individually; e.g., voltammetry with different potential programs can be measured on them [71]. A characteristic example of its use is the study of metal dissolution kinetics [72].

Surface charge density can be measured through the changes in surface stress that lead to small deformations [73]. A suitable optical arrangement called a “bending beam” has been assembled by Győző G. Láng recently; the method has been demonstrated on various systems [74].

With an optically transparent (e.g., ITO-based working electrode) of an EQCM, simultaneous measurement of surface mass changes, optical absorbance spectra, and voltammetry is possible. Such a combination has been implemented for the study of deposition and electrochemical transformations of polyaniline films by György Inzelt and coworkers [75]. Another electrode construction has been developed by Csaba Visy and coworkers by which simultaneous measurement of optical absorbance spectra, voltammetry, and conductivity of an electrochemically generated polymer film can be performed [76].

A bipotentiostat with a high dynamic range (i.e., with logarithmic current-to-voltage converters of 0.1 pA to 100 mA ranges) has been developed by Gábor Mészáros (RCNS IMEC) for various scanning microprobe measurements [77] and also for molecular conductance measurements [78]. About a dozen of these are in operation in Central-European research laboratories.

A dEIS (dynamic electrochemical impedance spectroscopy) measurement setup and the program has been developed by which audio-frequency impedance spectra can be taken repetitively at a fast rate which enables the taking of a number of impedance spectra during the run of cyclic voltammograms [79].

An electrochemical hydrogen permeation method, based on the measurement of the temporal evolution of the hydrogen breakthrough rate, has been elaborated by László Péter in the physics institute[4] for characterizing enamel-grade steel plate products. This method was implemented in 2003 at DUNAFERR, the largest steel company in Hungary at that time.

Monographs and handbooks

A few electrochemistry textbooks, handbooks, and monographs have been recently written by Hungarian authors. Perhaps the best known is the Electrochemistry Dictionary [2], one of the editors of which was György Inzelt. This book has had already two editions (in 2008 and an extended version in 2012); it is widely accepted and has received excellent reviews. This book, in fact, is an invaluable resource of knowledge of concepts, terms most used in electrochemistry, and the biography of scientists who greatly contributed to electrochemistry. It may serve as a reference for the whole electrochemist community.

Four monographs were written by Hungarian authors for a less broad professional field of interest. They are as follows, in the temporal order of their appearance:

The first, “Laser Techniques for the Study of Electrode Processes” [73], was co-authored by Győző G. Láng. Described therein are in situ techniques for the investigation of interfacial processes for those cases when there is surface geometry change due to the change of interfacial tension or there appears a refractive index gradient at the vicinity of a solid–liquid interface.

The second monograph, Handbook of Reference Electrodes [80], co-edited by György Inzelt, filled a half-century-old gap: since 1961 (when the last book on this subject appeared), many novel electrochemical systems appeared in the laboratory, which need appropriate reference electrodes.

The third book, “In situ Combined Electrochemical Techniques for Conducting Polymers” [81], is authored by Csaba Visy. This book surveys the advantages of combinations of in situ electrochemical techniques for analyzing the properties of conducting polymers.

The fourth monograph, “Electrochemical Methods of Nanostructure Preparation” [82], written by László Péter, summarizes the electrochemical routes of synthesizing nanostructures, including electrodeposition, anodization, carbon nanotube preparation, and other methods.

Two electrochemistry textbooks, in Hungarian, appeared in the past 2 decades [83, 84]. They both are used in universities for physical chemistry courses.

Summary and outlook

In the previous sections, a number of scientists have been mentioned by name. These are the colleagues who have (or had) smaller or larger groups, have done or have been doing electrochemical research typically for decades, and published enough to be "visible" when scientometric figures are considered. The name of their colleagues, in most cases, appears as co-authors in the publication list. In addition, there are many colleagues, not mentioned by name, who contributed to electrochemistry temporarily, worked, e.g., on industrial problems leading to no publication, or carried out the tiresome task of educating students to obtain basic laboratory skills. Also, these colleagues played an important role in maintaining the professional culture of electrochemistry.

The above list of topics reveals the continuity of research traditions in Hungary. On the one hand, the good news is that there are many researchers who deeply understand the structure of metal-electrolyte interfaces and the processes therein, along with their practical implications. The study of ion-selective electrodes was and still is important in electroanalysis. There are still inventive researchers who put together novel instruments. In three major universities, there are three young, ambitious, gifted electrochemist colleagues (Róbert E. Gyurcsányi, Soma Vesztergom, and Csaba Janáky, each holding a prestigious "Momentum" fellowship; Janáky has also an ERC grant); they can (and do) build up research groups with bright students. In addition, these three people are the ones who have strong international connections for cooperation, mostly in the USA, Switzerland, and elsewhere in Europe. The electroanalytical chemistry community is stable enough to run a conference series (the Mátrafüred International Conference on Electrochemical Sensors) since 1972.

On the other hand, unfortunately, the bad news is that, just as in the past, certain research areas are missing or are of low intensity, like the development of novel batteries and electrochemical technologies. Since the publication of [1] almost 3 decades ago, the number of electrochemical groups and scientists in Hungarian research sites has approximately halved. Funding has also decreased; brain drain from Western countries is strong; less and less students choose electrochemistry as a specialization. There are universities where, as there are no electrochemist faculty members, only the most necessary basic textbook knowledge is taught, and the students do not get the "hands-on" laboratory experience. Only a few students choose a Ph.D. topic related to electrochemistry. The lack of funding leads to the lack of appropriate instruments, in particular the facilities for the appropriate surface analyses.

As it is often claimed, the flourishing electrochemistry in Eastern Europe can be rationalized by the statement that electrochemistry is the "physical chemistry of the poor"; i.e., conducting electrochemical experiments is often the cheapest/simplest way to demonstrate physicochemical laws. Though Hungary is still not rich, electrochemistry apparently, is gradually losing its importance because of various reasons: One of the leading branches of electrochemistry, electroanalysis, including the various polarographic techniques, has been relegated to the background because better, more practical analytical methods (ICP and X-ray fluorescence) appeared. Several large-scale industries that require electrochemical background knowledge (e.g., aluminum electrolysis, light bulb production) have ceased to exist; other factory laboratories have also become unnecessary and hence were closed. Therefore, as need ceases, the money spent on laboratory education also decreases; instead, it is spent on teaching other "less expensive" skills, like computer simulations. At the same time, the general prestige of that particular discipline also decreases—even the electrochemist colleagues become prone to identify themselves as chemists dealing with nanoscience (or similar).

Nevertheless, the overall situation, though not very bright, is far from disappointing. Some industries occasionally may require electrochemical research to solve ad-hoc problems. During the application of new technologies, new corrosion problems always appear. Electrochemists might be needed to train the staff of the large battery factories planned for Hungary. These indicate that there will be a need for electrochemical research, knowledge, and education also in the future.

Funding Open access funding provided by ELKH Research Centre for Natural Sciences.

References

1. Inzelt G (2015) Hungarian comets in the sky of electrochemistry. In: Scholz F (ed) Electrochemistry in a Divided World. Innovations in Eastern Europe in the 20th Century. Springer, Heidelberg, pp 359–399

2. Bard AJ, Inzelt G, Scholz F (Eds) (2012) Electrochemical dictionary, 2nd Edition. Springer, Berlin-Heidelberg, ISBN 978-3-642-29550-8. https://doi.org/10.1007/978-3-642-29551-5
3. Lindner E, Tóth K (2009) To the memory of Ernő Pungor: a subjective view on the history of ion-selective electrodes. Electroanalysis 21:1887–1894. https://doi.org/10.1002/elan.200904624
4. Inzelt G (1996) Electrochemistry in Hungary. Electrochim Acta 41:vii–viii. https://doi.org/10.1016/S0013-4686(96)90173-5
5. Horányi G (1999) Radiotracer studies of adsorption/sorption phenomena at electrode surfaces. In: Wieckowski A (ed) Interfacial electrochemistry. Marcel Dekker, New York, p 477
6. Paszternák A, Felhősi I, Pászti Z et al (2009) Surface analytical characterization of passive iron surface modified by alkyl-phosphonic acid layers. Electrochim Acta 55:804–812. https://doi.org/10.1016/j.electacta.2009.09.023
7. Telegdi J, Rigó T, Pfeifer E et al (2008) Nanolayer coatings. Colloids for Nano-and. Biotechnology 135:77–86. https://doi.org/10.1007/2882_2008_098
8. Felhősi I, Telegdi J, Pálinkás G, Kálmán E (2002) Kinetics of self-assembled layer formation on iron. Electrochim Acta 47:2335–2340. https://doi.org/10.1016/S0013-4686(02)00084-1
9. Keresztes Z, Felhősi I, Kálman E (2001) Role of redox properties of biofilms in corrosion processes. Electrochim Acta 46:3841–3849. https://doi.org/10.1016/S0013-4686(01)00671-5
10. Felhősi I, Keresztes Z, Marek T, Pajkossy T (2020) Properties of electrochemical double-layer capacitors with carbon-nanotubes-on-carbon-fiber-felt electrodes. Electrochim Acta 334:135548. https://doi.org/10.1016/j.electacta.2019.135548
11. Bakos I, Szabó S (2001) Electrochemical adsorption of tin on palladium. Electrochim Acta 46:2507–2513. https://doi.org/10.1016/S0013-4686(01)00450-9
12. Szabó S, Bakos I (2001) Rhenium as an accelerator of iron corrosion. Corros Sci 43:931–938. https://doi.org/10.1016/S0010-938X(00)00110-4
13. Mészáros G, Szenes I, Lengyel B (2004) Measurement of charge transfer noise. Electrochem Comm 6:1185–1191. https://doi.org/10.1016/j.elecom.2004.09.017
14. Lendvay-Győrik G, Mészáros G, Lengyel B, Lendvay G (2003) Electrochemical and quantum chemical studies on the formation of protective films by alkynols on iron. Corros Sci 45:1685–1702. https://doi.org/10.1016/S0010-938X(03)00019-2
15. Lendvay-Győrik G, Pajkossy T, Lengyel B (2006) Corrosion-protection properties of water-borne paint coatings as studied by electrochemical impedance spectroscopy and gravimetry. Prog Org Coatings 56:304–310. https://doi.org/10.1016/j.porgcoat.2006.05.012
16. Fekete É, Lengyel B, Cserfalvi T, Pajkossy T (2016) Electrochemical dissolution of aluminium in electrocoagulation experiments. J Solid State Electrochem 20:3107–3114. https://doi.org/10.1007/s10008-016-3195-6
17. Pajkossy T (2018) Slow charging/discharging processes of the electrochemical double layer. Bulg Chem Comm 50D:90–98
18. Horváth V, Takécs T, Horvai G et al (1997) Anal Letters 30:1591–1609. https://doi.org/10.1080/00032719708001680
19. Gyurcsányi RE, Pergel E, Nagy R et al (2001) Direct evidence of ionic fluxes across ion selective membranes: a scanning electrochemical microscopic and potentiometric study. Anal Chem 73:2104–2111. https://doi.org/10.1021/ac000922k
20. Bereczki R, Takács B, Langmaier J et al (2006) How to assess the limits of ion-selective electrodes: method for the determination of the ultimate span, response range, and selectivity coefficients of neutral carrier-based cation selective electrodes. Anal Chem 78:942–950. https://doi.org/10.1021/ac050614s
21. Tóth K, Stulik K, Kutner W et al (2004) Electrochemical detection in liquid flow analytical techniques: characterization and classification - (IUPAC Technical Report). Pure Appl Chem 76:1119–1138. https://doi.org/10.1351/pac200476061119
22. Buck RP, Lindner E (2001) Tracing the history of selective ion sensors. Anal Chem 73:2A-11A
23. Pusztai S, Dankházi T, Farsang G (2003) The electrooxidation of halogeno-anilines at microelectrodes in acetonitrile solution. Electroanalysis 15:539–543. https://doi.org/10.1002/elan.200390066
24. Joó P (2004) Porosity and permeability of clay films: an electrochemical survey. In: Zrínyi M, Hórvölgyi ZD (eds) From colloids to nanotechnology. Progr Colloid Polym Sci 125:74–79. Springer (Berlin). https://doi.org/10.1007/b13922
25. Kiss IZ, Gáspár V, Nyikos L (1998) Stability analysis of the oscillatory electrodissolution of copper with impedance spectroscopy. J Phys Chem A 102:909–914. https://doi.org/10.1021/jp971984q
26. Kiss IZ, Nagy T, Gáspár V (2011) Dynamical instabilities in electrochemical processes. In: Kharton VV (ed) Solid State Electrochemistry II. https://doi.org/10.1002/9783527635566.ch4
27. Dombovári P, Kádár P, Kovács T et al (2007) Accumulation of uranium on austenitic stainless steel surfaces. Electrochim Acta 52:2542–2551. https://doi.org/10.1016/j.electacta.2006.09.007
28. Bujak R, Varga K (2006) In situ radiotracer and voltammetric study of the formation of surface adlayers in the course of Cr(VI) reduction on polycrystalline and (111) oriented platinum. Electrochim Acta 52:332–341. https://doi.org/10.1016/j.electacta.2006.05.012
29. Visy C, Lakatos M, Szücs Á, Novák M (1997) Separation of faradaic and capacitive current regions in the redox transformation of poly(3-methylthiophene) with the exclusion of overoxidation processes. Electrochim Acta 42:651–657. https://doi.org/10.1016/S0013-4686(96)00210-1
30. Kriván E, Visy C, Kankare J (2003) Deprotonation and dehydration of pristine PPy/DS films during open-circuit relaxation: an ignored factor in determining the properties of conducting polymers. J Phys Chem B 107:1302–1308. https://doi.org/10.1021/jp02146152003
31. Tóth PS, Peintler-Kriván E, Visy C (2012) Fast redox switching into the conducting state, related to single monocationic/polaronic charge carriers only in cation exchanger type conducting polymers. Electrochem Commun 18:16–19. https://doi.org/10.1016/j.elecom.2012.02.005
32. Endrődi B, Kormányos A, Janáky C et al (2014) Fixation of laccase enzyme into polypyrrole, assisted by chemical interaction with modified magnetite nanoparticles: a facile route to synthesize stable electroactive bionanocomposite catalysts. Electrochim Acta 122:282–288. https://doi.org/10.1016/j.electacta.2013.08.175
33. Inzelt G (2017) Recent advances in the field of conducting polymers. J Solid State Electrochem 21:1965–1975. https://doi.org/10.1007/s10008-017-3611-6
34. Inzelt G (2012) Conducting polymers–a new era in electrochemistry, Springer Berlin–Heidelberg. ISBN : 978-3-642-27620-0. https://doi.org/10.1007/978-3-642-27621-7
35. Ujvári M, Takács M, Vesztergom S et al (2011) Monitoring of the electrochemical degradation of PEDOT films on gold using the bending beam method. J Solid State Electrochem 15:2341–2349. https://doi.org/10.1007/s10008-011-1472-y
36. Ujvári M, Láng GG (2018) Electrochemical reduction of perchlorate ions. In: Wandelt K (ed) Encyclopedia of Interfacial Chemistry. pp 95–106. ISBN 9780128097397. https://doi.org/10.1016/B978-0-12-409547-2.13297-4
37. Galvez-Vazquez MD, Grozovski V, Kovács N et al (2020) Full model for the two-step polarization curves of hydrogen evolution, measured on RDEs in dilute acid solutions. J Phys Chem C 124:3988–4000. https://doi.org/10.1021/acs.jpcc.9b11337
38. Kovács N, Grozovski V, Vesztergom S (2020) A model for the faradaic efficiency of base metal electrodeposition from mildly acidic

baths to rotating disk electrodes. J Electrochem Soc 167:102510. https://doi.org/10.1149/1945-7111/ab975b

39. Kecsenovity E, Endrődi B, Tóth PS et al (2017) Enhanced photoelectrochemical performance of cuprous oxide/graphene nanohybrids. J Am Chem Soc 139:6682–6692. https://doi.org/10.1021/jacs.7b01820
40. Kormányos A, Kecsenovity E, Honarfar A et al (2020) Hybrid FeNiOOH/α-Fe2O3/graphene photoelectrodes with advanced water oxidation performance. Adv Func Mater 30:2002124. https://doi.org/10.1002/adfm.202002124
41. Scheidt RA, Samu GF, Janáky C, Kamat PV (2018) Modulation of charge recombination in CsPbBr 3 perovskite films with electrochemical bias. J Amer Chem Soc 140:86–89. https://doi.org/10.1021/jacs.7b10958
42. Pajkossy T (2020) Voltammetry coupled with impedance spectroscopy. J Solid St Electrochem 24:2157–2159. https://doi.org/10.1007/s10008-020-04689-w
43. Valiskó M, Kristóf T, Gillespie D, Boda D (2018) A systematic Monte Carlo simulation study of the primitive model planar electrical double layer over an extended range of concentrations, electrode charges, cation diameters and valences. AIP Adv 8:025320.https://doi.org/10.1063/1.5022036
44. Boda D (2014) Monte Carlo simulation of electrolyte solutions in biology: in and out of equilibrium. Ann Rep Comp Chem 10:127–163. https://doi.org/10.1016/B978-0-444-63378-1.00005-7
45. Vincze J, Valiskó M, Boda D (2010) The nonmonotonic concentration dependence of the mean activity coeffcient of electrolytes is a result of a balance between solvation and ion-ion correlations. J Chem Phys 133:154507.https://doi.org/10.1063/1.3489418
46. Boda D, Valiskó M, Gillespie D (2020) Modeling the device behavior of biological and synthetic nanopores with reduced models. Entropy 22:1259. https://doi.org/10.3390/e22111259
47. Jágerszki G, Takács Á, Bitter I, Gyurcsányi RE (2011) Solid-state ion channels for potentiometric sensing. Angew Chem Int Ed 50:1656–1659. https://doi.org/10.1002/anie.201003849
48. Makra I, Brajnovits A, Jágerszki G et al (2017) Potentiometric sensing of nucleic acids using chemically modified nanopores. Nanoscale 9:739–747. https://doi.org/10.1039/C6NR05886H
49. Terejánszky P, Makra I, Fürjes P et al (2014) Calibration-less sizing and quantitation of polymeric nanoparticles and viruses with quartz nanopipets. Anal Chem 86:4688–4697. https://doi.org/10.1021/ac500184z
50. Bognar Z, Supala E, Yarman A et al (2022) Peptide epitope-imprinted polymer microarrays for selective protein recognition. Application for SARS-CoV-2 RBD protein. Chem Sci 13:1263–1269. https://doi.org/10.1039/D1SC04502D
51. Filotás D, Fernández-Pérez BM, Izquierdo J et al (2016) Combined amperometric/potentiometric probes for improved chemical imaging of corroding surfaces using scanning electrochemical microscopy. Electrochim Acta 221:48–55. https://doi.org/10.1016/j.electacta.2016.10.142
52. Kiss L, Őri Z, Nagy L et al (2013) Voltammetric concentration measurements in diffusion hindered media. J Solid State Electrochem 17:3039–3045. https://doi.org/10.1007/s10008-013-2178-0
53. Kriston Á, Inzelt G (2008) Estimation of the characteristic parameters of proton exchange membrane fuel cells under normal operating conditions. J Appl Electrochem 38:415–424. https://doi.org/10.1007/s10800-007-9454-6
54. Dobosy P, Vizsolyi ÉC, Varga I et al (2016) Trichloroethylene removal from water by ferrate treatment. Microchem J 127:74–78. https://doi.org/10.1016/j.microc.2016.02.010
55. Láng GG, Varga J, Záray G, Varga IP (2020) Equipment and procedure for the preparation of sodium and potassium ferrate solutions by electrochemical method (Berendezés és eljárás nátrium- és kálium-ferrát oldatok elektrokémiai módszerrel történő előállítására), Hungarian patent, registration number 231043 case number P1600474
56. Bakonyi I, Tóth-Kádár E, Tarnóczi T et al (1993) Structure and properties of fine-grained electrodeposited nickel. Nanostruct Mater 3:155–161
57. Bakonyi I, Péter L (2010) Electrodeposited multilayer films with giant magnetoresistance (GMR): progress and problems. Prog Mat Sci 55:107–245. https://doi.org/10.1016/j.pmatsci.2009.07.001
58. Péter L, Vad K, Csik A et al (2018) (2018) In-depth component distribution in electrodeposited alloys and multilayers. J Electrochem Sci Eng 8:49–71. https://doi.org/10.5599/jese.480
59. Péter L, Fekete É, Kapoor G, Gubicza J (2021) Influence of the preparation conditions on the microstructure of electrodeposited nanocrystalline Ni–Mo alloys. Electrochim Acta 382:138352. https://doi.org/10.1016/j.electacta.2021.138352
60. Nagy G, Kerner Z, Balog J, Schiller R (2007): High temperature electrochemical impedance spectroscopy of metals related to light water reactor corrosion. In: R.-W. Bosch R-W, Féron D, Celis J-P (eds) Electrochemistry in light water reactors. CRC Press, Boca Raton and Woodhead Publishing Limited, Cambridge
61. Kerner Z, Balog J, Nagy G (2006) Testing of high temperature reference electrodes for light water reactor applications. Corr Sci 48:1899–1911
62. Tury B, Lakatos-Varsanyi M, Roy S (2006) Ni-Co alloys plated by pulse currents. Surf Coat Technol 200:6713–6717. https://doi.org/10.1016/j.surfcoat.2005.10.008
63. Furkó M, Lakatos-Varsanyi M, Balázsi C (2016) Complex electrochemical studies on silver-coated metallic implants for orthopaedic application. J Solid State Electrochem 20:263–271. https://doi.org/10.1007/s10008-015-3026-1
64. Lukács Z, Molnár F, Kovács I et al (2020) Corrosion testing and evaluation of gas oil desulfurization reactor structure material in the presence of fatty acids, Eng Fail Anal 107:104221.https://doi.org/10.1016/j.engfailanal.2019.104221
65. Lukács Z, Baccilieri D, Hancsók J, Kristóf T (2021) A dispersion-invariant model of the electrochemical impedance. Electrochim. Acta 390:138828. https://doi.org/10.1016/j.electacta.2021.138828
66. Endrődi B, Kecsenovity E, Samu A et al (2019) Multilayer electrolyzer stack converts carbon dioxide to gas products at high pressure with high efficiency. ACS Energy Lett 4:1770–1777. https://doi.org/10.1021/acsenergylett.9b01142
67. Endrődi B, Samu A, Kecsenovity E et al (2021) Operando cathode activation with alkali metal cations for high current density operation of water-fed zero-gap carbon dioxide electrolysers. Nat Energy 6:439–448. https://doi.org/10.1038/s41560-021-00813-w
68. Gubán D, Tompos A, Bakos I et al (2017) Preparation of CO-tolerant anode electrocatalysts for polymer electrolyte membrane fuel cells. Int J Hydrogen Energy 42:13741–13753. https://doi.org/10.1016/j.ijhydene.2017.03.080
69. Bakos I, Borbáth I, Vass Á et al (2018) Design and investigation of molybdenum modified platinum surfaces for modeling of CO tolerant electrocatalysts. Top Catal 61:1385–1395. https://doi.org/10.1007/s11244-018-1035-x
70. Medgyes B, Illés B, Harsányi G (2012) Electrochemical migration behaviour of Cu, Sn, Ag and Sn63/Pb37. J Mat Sci Mater Electron 23:551–556. https://doi.org/10.1007/s10854-011-0435-5
71. Vesztergom S, Ujvári M, Láng GG (2013) Dual cyclic voltammetry with rotating ring-disk electrodes. Electrochim Acta 110:49–55. https://doi.org/10.1016/j.electacta.2013.01.142
72. Kovács N, Sziráki L, Vesztergom S, Láng GG (2018) Investigating products of titanium dissolution in the presence of fluoride ions with dual dynamic voltammetry. J Electrochem Sci Eng 8:141–149. https://doi.org/10.5599/jese.502
73. Láng GG, Barbero C (2012) Laser techniques for the study of electrode processes. In: Scholz F (ed) Monographs in electrochemistry, Springer: New York
74. Láng GG, Kovács N, Vesztergom S et al (2017) Experimental methods for the determination of stress changes at electrified

solid-liquid, interfaces. Tech Mess 84:644–658. https://doi.org/10.1515/teme-2016-0082

75. Berkes BB, Vesztergom S (2013) Inzelt G (2013) Combination of nanogravimetry and visible spectroscopy: a tool for the better understanding of electrochemical processes. J Electroanal Chem 719:41–46. https://doi.org/10.1016/j.jelechem.2014.01.031
76. Peintler-Kriván E, Tóth PS, Visy C (2009) Combination of in situ UV–Vis-NIR spectro-electrochemical and a.c. impedance measurements: a new, effective technique for studying the redox transformation of conducting electroactive materials. Electrochem Comm 11:1947–1950. https://doi.org/10.1016/j.elecom.2009.08.025
77. Mészáros G, Li C, Pobelov I, Wandlowski T (2007) Current measurements in a wide dynamic range—applications in electrochemical nanotechnology. Nanotechnology 18:424004. https://doi.org/10.1088/0957-4484/18/42/424004
78. Vavrek F, Butsyk O, Kolivoška V et al (2021) Does the seebeck coefficient of single molecule junctions depend on the junction configuration? J Mater Chem A 9:17512–17520
79. Pajkossy T, Mészáros G (2020) Connection of CVs and impedance spectra of reversible redox systems, as used for the validation of a dynamic electrochemical impedance spectrum measurement system. J Solid St Electrochem 24:2883–2889. https://doi.org/10.1007/s10008-020-04661-8
80. Inzelt G, Lewenstam A, Scholz F (eds) (2013) Handbook of reference electrodes. Springer, Berlin, ISBN 978-3-642-36187-6)
81. Visy C (2017) In situ combined electrochemical techniques for conducting polymers. Springer Cham. https://doi.org/10.1007/978-3-319-53515-9
82. Péter L (2021) Electrochemical methods of nanostructure preparation. Springer Cham. ISBN:978-3-030-69116-5. https://doi.org/10.1007/978-3-030-69117-2
83. Inzelt G (1999) Modern theories and methods of electrochemistry (in Hungarian: Az elektrokémia korszerű elmélete és módszerei). Nemzeti Tankönyvkiadó, Budapest. Vol I. pp 297, ISBN: 963-18-9100-3, Vol II. pp 326, ISBN: 963-19-0183-1
84. Kiss L, Láng GG (2011) Electrochemistry (in Hungarian: Elektrokémia). Semmelweis Kiadó, Budapest. Pp 260, ISBN:9789633311479