

Author's statement on the original scientific contributions of the works submitted by Assoc. Prof. Jenia Stefanova Georgieva in the competition

The research activity presented in the current competition is focused on the development, optimization, and comprehensive characterization of nanostructured electro- and photoelectrocatalytic materials for applications in fuel cells, electrolyzers, and photoelectrochemical systems. A primary emphasis of the research is the elucidation of the relationships between the composition, structure, and morphology of catalytic materials and their electrocatalytic activity and stability.

A significant contribution of the research is the development of original, low-temperature, and environmentally friendly approaches for the synthesis of nanostructured catalysts based on the combination of electroless chemical deposition, photochemical reduction, and galvanic replacement. These approaches build upon the accumulated expertise in electroless deposition and the control of multicomponent metallic coating formation, providing the methodological foundation for the subsequent development of nanostructured electrocatalysts with controlled composition and architecture (*Publication 7.10*). These methods enabled precise control over the composition, size, and dispersion of the active phase. The obtained results demonstrate that the combined synthesis strategies lead to the formation of catalytic nanoparticles with a core-shell structure, consisting of a non-noble metal core (Cu, Ni, or Co) and a Pt-enriched shell, thereby simultaneously reducing the amount of noble metal required while improving its utilization efficiency. By controlling the synthesis conditions, the degree of alloying and the electronic properties of Pt were systematically tailored. Furthermore, the application of galvanic replacement was extended to semiconductor oxides and nanostructured supports, demonstrating the possibility of the controlled fabrication of functional catalytic architectures with optimized active-phase distribution. Structure-activity relationships governing the behavior of the catalytic systems in the electrooxidation of organic compounds, as well as in oxygen reduction and oxygen evolution reactions, were established. The role of electronic interactions between metallic nanoparticles and the support, together with metal-metal and metal-oxide interactions, was elucidated with respect to tuning adsorption properties, poisoning resistance, and long-term electrochemical stability.

The research has been carried out within the framework of long-standing international scientific collaboration with leading research groups at Aristotle University of Thessaloniki (Greece), Vrije Universiteit Brussel (Belgium), CEST Kompetenzzentrum für elektrochemische Oberflächentechnologie GmbH (Austria), and Institut Charles Gerhardt Montpellier (France). These collaborations have substantially contributed to the interdisciplinary nature of the research and to the international recognition of the achieved results.

The scientific publications submitted for the competition are fully aligned with one of the major research priorities of the Institute of Physical Chemistry, Bulgarian Academy of Sciences, namely the development of advanced materials and technologies based on electrochemically produced metallic, alloy, and modified polymer coatings possessing protective, decorative, and electrocatalytic properties.

A total of 20 scientific publications published in international peer-reviewed journals indexed in internationally recognized scientific databases have been submitted for the competition. Of these, 8 publications constitute the habilitation work, including 6 papers published in Q1 journals and 2 in Q2 journals. In addition, 12 publications outside the habilitation work are included, distributed as follows: 7 in Q1 journals, 1 in a Q2 journal, 2 in Q3 journals, and 2 publications in peer-reviewed journals indexed in SJR but without an IF. The results have been presented at 25 national and international scientific conferences, and part of the reported work was carried out within the framework of 9 national and international research projects. By the date of the competition announcement, these publications had received a total of 546 citations (excluding self-citations by co-authors), comprising 210 citations of the publications included in the habilitation work and 336 citations of the publications outside the habilitation work.

To date, the overall scientific output comprises 55 publications, of which 51 have been published in international peer-reviewed journals: 36 in Q1 journals, 4 in Q2 journals, 5 in Q3 journals, 1 in a Q4 journal, 1 book chapter, and 4 publications in SJR-indexed journals without an IF. The research findings have been presented at numerous international and national scientific conferences. A substantial part of these results has been obtained through the implementation of national and international research projects. The author's Scopus h-index is 25. The volume and citation impact of the scientific output demonstrate sustained development of the research activity and broad international recognition of the scientific contributions.

The accumulated scientific expertise in the development of electrocatalysts by galvanic replacement and in photoelectrocatalytic processes has been summarized and critically analyzed in two review articles, which systematically examine the progress achieved in these research areas, discuss their advantages and limitations, and outline future perspectives for their application. These reviews have contributed to the international visibility of the developed methodological approaches and have further established the scientific direction pursued by the research team (*Publications 7.8 and 7.9*).

The original scientific contributions of the works submitted for the competition may be grouped into the following major thematic areas:

1. Electrocatalytic Methanol Oxidation (MOR)

1.1. Structural Factors and Mechanisms Governing Electrocatalytic Activity toward MOR

A major scientific contribution of the research is the establishment of the relationships between the composition, structure, morphology, and electrocatalytic activity of Pt-based catalytic systems for the methanol oxidation reaction (MOR). It was demonstrated that the catalytic activity is governed by the balance and synergistic interactions among the active metallic phase, the oxide support, and the conductive carbon phase, as well as by the electronic interactions between these components.

A comprehensive combination of structural, spectroscopic, and electrochemical techniques—including scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS), transmission electron microscopy (TEM), X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), cyclic voltammetry (CV), linear sweep voltammetry

(LSV), chronoamperometry (CA), and electrochemical impedance spectroscopy (EIS)—was employed to elucidate the factors determining the activity and stability of the catalytic materials. The results revealed that the size, dispersion, and morphology of the metallic nanoparticles, together with the nature of the support, exert a significant influence on the electrochemically active surface area, reaction kinetics, and resistance to poisoning by CO-containing reaction intermediates.

For the Pt(Cu)/C systems, TEM investigations revealed partial alloying between Pt and Cu together with the formation of core-shell nanostructures consisting of a Cu-containing core and a Pt-enriched shell. This structure results from the partial galvanic replacement of chemically deposited Cu on a carbon support by Pt. It was established that the composition and chemical state of the copper phase, including the presence of Cu₂O/CuO species, govern both the galvanic replacement process and the final structural characteristics of the catalytic material (*Publications 4.1 and 4.3*).

Subsequent studies investigated the influence of the Pt(Cu) nanoparticle structure on catalytic activity. TEM and spectroscopic analyses demonstrated the formation of a protective Pt-enriched shell surrounding a Cu-containing core, which accounts for the high intrinsic catalytic activity toward CO and methanol oxidation. At the same time, particle agglomeration and the limited electrochemically active surface area were shown to reduce the mass activity, thereby identifying the principal directions for further optimization of the synthesis procedure (*Publication 7.12*).

For Pt(Ni)/C catalysts prepared by sequential electroless deposition of Ni followed by galvanic replacement with Pt, the formation of a complex hierarchical structure was established. This architecture consists of a Pt-enriched outer shell and a particle core composed of a Pt–Ni alloy containing small Ni-rich domains (*Publication 4.2*).

Subsequent studies, conducted outside the habilitation work, demonstrated that the interaction between Pt and oxide supports plays a decisive role in determining the catalytic properties. For Pt(Ni)/TiO₂ and Pt(Ni)/TiO₂–C systems, the enhanced catalytic performance was found not to originate from the formation of substantial amounts of Pt–Ni alloy but primarily from the synergistic interaction between Pt nanoparticles and the TiO₂ support. XPS and anomalous small-angle X-ray scattering (ASAXS) analyses revealed the formation of well-dispersed Pt nanoparticles with diameters of 1.5–2.1 nm, distributed over both the TiO₂ phase and the carbon regions of the composite support. Both Pt(Ni)/TiO₂ and Pt(Ni)/TiO₂–C exhibited higher intrinsic catalytic activity toward CO and methanol oxidation than the commercial Pt/C catalyst, owing to the synergistic interaction between Pt nanoparticles and TiO₂. As a consequence of the synthesis strategy employed, this effect was more pronounced for the Pt(Ni)/TiO₂ catalyst, which exhibited the highest intrinsic catalytic activity. Nevertheless, the mass-specific activity of both catalysts remained lower than that of Pt/C because of the higher degree of Pt nanoparticle agglomeration and the lower specific surface area (*Publication 7.2*).

Composite Pt–WO₃ and Pt–TiO₂/WO₃ systems were also investigated in order to clarify the role of semiconductor components in improving the electronic properties and stability of the catalysts. It was demonstrated that combining metallic and semiconductor phases enhances the electrocatalytic activity toward MOR and facilitates the removal of the poisoning intermediate CO adsorbed on Pt through photoinduced processes (*Publications 7.1 and 7.6*).

1.2. Synergistic Effects between Pt, Transition Metals, and the Support: Enhancement of Catalytic Activity and Stability

Bimetallic Pt(Cu) and Pt(Ni) electrocatalysts supported on carbon, oxide, and composite materials were developed by combining electroless deposition, photochemical reduction, and galvanic replacement. It was demonstrated that the incorporation of transition metals induces significant electronic and geometric effects, which modify the electronic structure of Pt and optimize the adsorption–desorption processes involved in the MOR.

For Pt(Cu)/TiO₂ systems prepared by photochemical deposition followed by galvanic replacement, an approximately six-fold increase in intrinsic catalytic activity was achieved compared with a commercial Pt/C catalyst. Combined transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDS) analyses revealed the formation of a Pt-enriched surface layer surrounding a Cu-containing core, providing a protective effect for the platinum phase. The enhanced catalytic performance was attributed both to the formation of Pt(Cu) nanostructures and to the specific interaction between the metallic phase and the TiO₂ support (*Publications 7.4 and 7.5*).

By combining experimental investigations with theoretical calculations, the relationship between the nanocomposite structure, the electronic interactions within the catalytic phase, and the catalytic activity toward MOR was established for PtCu@TiO₂ systems. These studies elucidated the role of metal–oxide interactions in the formation of catalytically active sites and provided a molecular-level explanation of the observed synergistic effects (*Publication 7.5*).

It was further demonstrated that Pt–TiO₂–C composite systems exhibit enhanced stability during the photoelectrochemical oxidation of methanol. Under UV irradiation, the catalytic activity increased by approximately 25% as a result of the photoactivation of TiO₂ and the facilitated removal of adsorbed reaction intermediates by photogenerated hydroxyl radicals ([•]OH) (*Publication 4.7*).

The mechanisms of CO poisoning and strategies for improving the durability of Pt-based catalysts were also investigated. It was established that modification of Pt with transition metals, together with its combination with oxide supports, decreases the CO binding strength and facilitates the oxidation of adsorbed reaction intermediates compared with conventional Pt/C catalysts. This effect is evidenced by the shift of the CO oxidation potential toward lower values (*Publications 4.1, 4.3, 7.2, 7.4, 7.12*).

Scientific Novelty

Structure–activity relationships have been established for Pt-based catalysts used in the electro- and photoelectrochemical oxidation of methanol, elucidating the influence of catalyst composition, morphology, and support nature on catalytic activity and stability.

Nanostructured bimetallic Pt(Cu) and Pt(Ni) electrocatalysts supported on carbon, oxide, and composite materials have been developed by combining electroless deposition, photochemical reduction, and galvanic replacement, enabling the efficient utilization of the noble metal.

The key role of metal–support interactions in Pt/TiO₂, Pt/WO₃, and composite catalytic systems has been demonstrated in governing the electronic properties, CO tolerance, and electrocatalytic stability of the catalysts.

The mechanisms underlying the synergistic interactions between metallic nanoparticles and semiconductor oxide components have been elucidated, including the participation of photogenerated charge carriers in photoelectrocatalytic processes.

Novel approaches have been proposed for the preparation of highly efficient electrocatalysts with reduced noble-metal content through the controlled formation of nanostructured metallic and metal–oxide systems.

2. Electrocatalytic Reactions Involving Oxygen (ORR and OER)

Within this research direction, the work has focused on the development of nanostructured electrocatalytic systems with reduced noble metal content and on elucidating the relationship between the synthesis method, the structure of the active phase, metal–support interactions, and catalytic performance. A major objective has been to extend the approaches developed in the habilitation work for the controlled preparation of bimetallic catalytic systems by chemical deposition followed by galvanic displacement toward the use of oxide supports, photochemical synthesis methods, and the preparation of electrocatalysts for oxygen-related reactions.

2.1. Development of Nanostructured Catalytic Systems on Oxide Supports

Pt-based electrocatalysts supported on oxide materials were developed in order to investigate the role of the support in the formation of the active phase, its dispersion, and its electrocatalytic properties. Pt(Ni) electrocatalysts supported on TiO₂ and TiO₂–C were synthesized by chemical deposition followed by galvanic displacement (*Publication 7.2*). It was demonstrated that the interaction between the platinum phase and the oxide support has a significant influence on the structure of the active sites and the catalytic activity.

These approaches were further extended to Pt(Cu)/TiO₂ nanostructured systems prepared by combining photochemical deposition with galvanic displacement (*Publication 7.4*). This strategy enables the controlled formation of highly dispersed bimetallic nanoparticles and the efficient utilization of the noble metal. The studies were subsequently expanded through a detailed investigation of PtCu@TiO₂ nanocatalysts, establishing the relationship between the structural characteristics of the active phase and the electrocatalytic activity (*Publication 7.5*).

It was demonstrated that oxide supports perform not only a structural function but also actively regulate the electronic properties and stability of the catalytic systems. This was further confirmed for Pt-doped TiO₂/WO₃ bilayer catalytic structures exhibiting enhanced photoelectrocatalytic activity toward methanol oxidation under visible-light irradiation (*Publication 7.6*). In addition, modified TiO₂ nanotube structures with improved photoelectrochemical properties were developed through controlled boron and nitrogen doping (*Publication 7.3*).

These results represent a further development of the methodological framework established in the habilitation work, where approaches for preparing bimetallic Pt-based catalysts through the deposition of a transition metal followed by galvanic displacement with Pt were originally developed. In the subsequent studies, these strategies were expanded through

the incorporation of oxide supports and photochemical synthesis methods, enabling the preparation of catalytic systems with controlled structure and enhanced performance.

2.2. Nanostructured ORR and OER Catalysts with Reduced Noble Metal Content

The developed approaches for the controlled preparation of bimetallic nanostructures were successfully applied to the synthesis of electrocatalysts for the oxygen reduction reaction (ORR). Pt–Cu/C and Pt–Co/C electrocatalysts with reduced noble metal content and improved electrocatalytic performance were prepared by chemical deposition of Cu or Co onto carbon supports, followed by partial galvanic displacement with Pt.

For the Pt–Cu/C electrocatalysts, it was demonstrated that alloying Pt with Cu modifies the electronic structure of the active phase and improves the kinetics of the oxygen reduction reaction. The Pt–Cu/C catalyst exhibited up to 56% higher specific activity than a commercial Pt/C catalyst at 0.85 V versus the reversible hydrogen electrode (RHE), owing to the electronic interactions between Cu and the surface Pt atoms (*Publication 4.4*).

The developed Pt–Co/C electrocatalysts contained a low Co loading (approximately 0.7 wt.%). TEM and spectroscopic analyses confirmed the formation of a Co–Pt core–shell structure. Despite their lower electrochemically active surface area, these catalysts exhibited approximately 2.6 times higher mass activity and four times higher intrinsic catalytic activity than a commercial Pt/C catalyst at 0.85 V versus RHE. These findings demonstrate that the noble metal content can be significantly reduced while simultaneously improving catalytic performance (*Publication 4.8*).

For the oxygen evolution reaction (OER), highly dispersed IrO₂/TiO₂ catalytic systems with reduced Ir loading were developed. An original low-temperature photochemical synthesis route enabled the direct formation of IrO₂ nanoparticles on the TiO₂ support. Uniformly dispersed IrO₂ nanoparticles with a size of 1–2 nm and an Ir loading of 25 wt.% were obtained. The resulting catalysts exhibited intrinsic catalytic activity comparable to that of a commercial IrO₂ catalyst despite the substantially lower noble metal content. Comprehensive characterization by CV, EIS, and XPS demonstrated that the enhanced OER activity of the IrO₂/TiO₂ catalysts is determined not only by the electrochemically active surface area but also by the increased intrinsic catalytic activity of IrO₂ resulting from strong IrO₂–TiO₂ interactions and the high dispersion of the active phase (*Publications 4.5 and 4.6*). It was further established that UV irradiation improves the stability of the IrO₂/TiO₂ catalysts during the oxygen evolution reaction, most likely owing to the prolonged participation of photogenerated holes and hydroxyl radicals. Simultaneously, an increase in current density was observed as a result of the interaction between photogenerated holes in the TiO₂ support and the IrO₂ nanoparticles. These findings demonstrate the potential of the developed catalytic systems for long-term photoelectrochemical water splitting applications (*Publication 4.5*).

Scientific Novelty

A systematic strategy was developed for the preparation of nanostructured electrocatalysts with reduced noble metal content, based on the controlled formation of the active phase, the utilization of bimetallic interactions, and the optimization of metal–support interactions.

The synthesis methodologies for Pt-based catalytic systems were extended through the introduction of oxide supports and photochemical approaches, enabling the preparation of highly dispersed nanostructures with enhanced electrocatalytic performance.

The functional role of TiO₂ and WO₃ oxide supports in regulating the dispersion, electronic properties, stability, and catalytic activity of the active phase was established.

Pt–Cu/C, Pt–Co/C, and IrO₂/TiO₂ electrocatalytic systems for the oxygen reduction and oxygen evolution reactions were developed, achieving a significant reduction in noble metal content while maintaining or improving catalytic performance.

The obtained results define an independent research direction focused on the development of highly efficient electrocatalysts through the rational control of the structural and electronic factors governing catalytic activity and long-term stability.

3. Electro- and Photoelectrocatalytic Processes on Oxide Supports and Composite Materials

Following the habilitation work, the research has been directed toward the development of electro- and photoelectrocatalytic systems based on oxide semiconductors and metal–oxide composites, with the primary objective of elucidating the relationship between the structure of the materials, charge generation and transport processes, and catalytic activity. Novel approaches have been proposed for the modification of TiO₂ and WO₃, the preparation of metal–oxide composite systems, and the control of interactions between the metallic and oxide phases. These studies represent a natural continuation of the methodologies developed in the habilitation work for the preparation of nanostructured metallic electrocatalysts by chemical deposition and galvanic displacement. In the subsequent research, these approaches were extended to semiconductor supports and photochemical processes, enabling control over the electronic structure, charge separation, and functional properties of catalytic materials.

A methodological approach was developed for the quantitative evaluation of the intrinsic photoelectrocatalytic activity of TiO₂ photoanodes through the combined use of parameters derived from electrochemical impedance spectroscopy (Q_{dl} and $R_{et}Q_{dl}$). It was demonstrated that this approach makes it possible to distinguish the contribution of the specific surface area from the intrinsic photoelectrocatalytic activity of the material, thereby providing a reliable criterion for comparing different types of TiO₂ photoanodes. TiO₂ nanotube photoanodes, despite their lower intrinsic photoelectrochemical activity, exhibited higher photocurrent densities and greater efficiency for chloramphenicol degradation than sol–gel TiO₂ photoanodes owing to their substantially larger specific surface area (*Publication 7.7*).

3.1. Photoelectrocatalytic Methanol Oxidation and the Role of Photogenerated Charge Carriers

Within this research direction, photoelectrocatalytic systems based on TiO₂, WO₃, and metal-modified oxide materials were developed for methanol oxidation. The principal scientific contribution lies in elucidating the role of photogenerated charge carriers and the interplay between photocatalytic and electrocatalytic processes.

Early investigations demonstrated that the electrocatalytic and photoelectrocatalytic activity of Pt/TiO₂ systems depends both on the interaction between Pt and the semiconductor support and on the crystalline phase of TiO₂ (anatase or rutile). It was shown that the nature of the support governs the efficiency of photoinduced processes as well as the electrocatalytic oxidation of methanol under both dark conditions and UV irradiation, thereby establishing the foundation for the subsequent development of Pt/TiO₂-based photoelectrocatalytic systems (*Publication 7.11*).

For Pt–TiO₂–C systems, UV irradiation was shown to increase the catalytic activity by approximately 25% owing to the photoactivation of TiO₂ and the suppression of active-site poisoning by reaction intermediates (*Publication 4.7*).

For Pt/WO₃ electrocatalysts, it was demonstrated that combining the metallic phase with a photosensitive oxide component significantly enhances catalytic performance. The synergistic action of Pt and WO₃ resulted in nearly a three-fold increase in intrinsic catalytic activity for methanol electrooxidation compared with a commercial Pt/C catalyst (*Publication 7.1*). Under visible-light irradiation, photogenerated holes and oxygen-containing reactive species facilitate the removal of CO adsorbates from the Pt surface, producing a photoinduced self-cleaning effect of the catalytic surface.

The investigation of photoelectrochemical processes further demonstrated that photogenerated electrons and holes participate directly in the electrode reactions. Photogenerated holes promote oxidation reactions, whereas photogenerated electrons drive reduction processes and charge transport. A pronounced synergistic effect between light irradiation and the applied electrode potential was established, whereby suppression of electron–hole recombination leads to enhanced catalytic efficiency.

3.2. Modification of TiO₂ for Enhanced Photoelectrochemical Properties

Modified TiO₂ nanostructures (nanotubes) were developed through simultaneous boron and nitrogen doping in order to improve photoelectrochemical activity and extend spectral sensitivity into the visible-light region. An original, environmentally friendly, and straightforward method was employed for the controlled incorporation of the dopant elements into the oxide structure (*Publication 7.3*). Comprehensive structural, spectroscopic, and electrochemical characterization demonstrated that the introduction of B and N modifies the electronic structure of TiO₂ by generating additional electronic states within the band gap. These modifications facilitate visible-light excitation and improve the efficiency of electron–hole pair generation and separation.

The modified TiO₂ systems exhibited higher photoelectrochemical activity than undoped TiO₂ under both UV and visible-light irradiation. Co-doping with boron and nitrogen was found to promote more efficient separation of photogenerated electrons and holes while suppressing recombination processes. These findings were confirmed through photoelectrocatalytic degradation of methyl orange, demonstrating the synergistic effect of the two dopants on the activity of TiO₂ nanotubes (*Publication 7.3*).

3.3. Photochemical Synthesis and Metal–Oxide Interactions in Composite Systems

Photochemical approaches were developed for the preparation of metal–oxide composite materials containing Pt, Cu, and IrO₂ on TiO₂-based supports. These studies further

expanded the methodologies for the controlled formation of metallic nanostructures originally established in the habilitation work.

Highly dispersed Pt(Cu)/TiO₂ catalytic systems with controlled distribution of the active phase were prepared by combining photodeposition with galvanic displacement. An original mechanism for the formation of the metallic phase was proposed, involving the simultaneous occurrence of galvanic displacement of Cu by Pt and Ti(III)/Ti(IV) redox transitions within TiO₂. It was demonstrated that Ti(III) centers participate directly in the reduction of Pt ions and the formation of the active metallic phase. The resulting Pt(Cu)/TiO₂ catalysts exhibited approximately six-fold higher intrinsic catalytic activity toward methanol electrooxidation than a commercial Pt/C catalyst (*Publication 7.4*).

These findings were further extended through a detailed investigation of PtCu@TiO₂ nanocatalysts, in which combined structural characterization and theoretical analyses established the relationship between catalyst composition, the electronic state of the active sites, and catalytic activity (*Publication 7.5*). In addition, Pt-doped TiO₂/WO₃ bilayer systems with enhanced photoelectrocatalytic activity for methanol oxidation were developed (*Publication 7.6*).

The obtained results demonstrate that metal–oxide interactions are a key factor governing the electronic structure, stability, and catalytic properties of composite materials.

Scientific Novelty

A synergistic mechanism between photocatalytic and electrocatalytic processes during the oxidation of organic compounds on TiO₂- and WO₃-based systems was established, and the role of photogenerated charge carriers in enhancing catalytic activity was elucidated.

Modified TiO₂ nanostructures co-doped with boron and nitrogen were developed, resulting in tailored electronic structure, improved charge-carrier separation, and enhanced photoelectrochemical activity.

For the first time, a mechanism for the formation of Pt(Cu)/TiO₂ composite catalysts was proposed, demonstrating the crucial role of Ti(III)/Ti(IV) redox transitions in the formation and stabilization of the active metallic phase.

It was established that metal–oxide interactions govern the electronic and structural characteristics of composite materials and represent a key factor in achieving high catalytic activity and long-term stability.

A comprehensive concept was developed for controlling the electrocatalytic and photoelectrocatalytic properties of catalytic materials through the integration of metallic nanoparticles, semiconductor oxides, and controlled photochemical synthesis.

Conclusion

In summary, the conducted research has established a coherent methodological framework for the rational control of the composition, structure, and electronic properties of Pt-based electrocatalytic systems through the combination of chemical deposition, photochemical reduction, and galvanic displacement. An effective strategy has been developed for the preparation of nanostructured catalysts with reduced noble metal content, based on the

controlled formation of core–shell architectures and the optimization of interactions between the active phase and the support while maintaining or enhancing catalytic performance.

The obtained results significantly expand the fundamental understanding of the role of metal–metal and metal–oxide interactions in electro- and photoelectrocatalytic processes, clarify the mechanisms governing catalytic activity and stability, and provide a scientific foundation for the development of highly efficient electrocatalysts for applications in fuel cells, water electrolyzers, and photoelectrochemical energy conversion systems.