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Research paper

Laser-Enhanced Electrochemical Performance of an Aluminium–Air Cell with a Gold Cathode in Artificial Tear Electrolyte

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Abstract

Smart contact lenses, as an emerging class of wearable devices, require lightweight, safe, and biocompatible power sources capable of operating in the ocular environment. Aluminum–air batteries represent a promising candidate due to their high energy density and favorable biocompatibility, yet their performance in near-neutral conditions remains limited by the sluggish kinetics of the oxygen reduction reaction (ORR). In this work, we experimentally investigate the effect of optical stimulation on the performance of an aluminum–air cell with a gold cathode in artificial tear electrolyte under 532 nm green-laser illumination. Cyclic voltammetry (CV), galvanostatic discharge (GCD), and electrochemical impedance spectroscopy (EIS) were employed to compare the battery behavior in laser-off and laser-on states. The results show that laser illumination significantly enhances the cathodic peak current, increases the discharge capacity by approximately 15%, and reduces the charge-transfer resistance by more than 60%. These concurrent improvements demonstrate that optical stimulation can effectively strengthen cathodic activity and charge-transfer pathways, thereby supporting the development of biocompatible power sources based on aluminum–air systems.

1. Introduction

Smart contact lenses have emerged in recent years as a promising platform for real-time monitoring of ocular conditions. These devices enable the integration of miniature sensors, communication modules, and lightweight electronic components into a soft and biocompatible interface that can operate without interfering with the user's normal vision or comfort [1], [2], [3]. Despite these advantages, providing a safe, stable, and on-eye power source remains one of the most critical challenges for practical deployment [2], [4]. Consequently, electrolytes compatible with the ocular environment particularly tear-based or tear-activated systems have attracted increasing attention, and several studies have explored aqueous or tear-compatible batteries for smart contact lenses

[4], [5]. Among energy storage technologies, metal-air batteries exhibit significant promise for lightweight, wearable applications due to their high theoretical energy density and relatively simple configuration [6]. Aluminum-air (Al-air) batteries, leveraging the abundance, low cost, biocompatibility, and favorable energy capacity of aluminum, represent a compelling option for near-body devices such as smart lenses.[7], [8]. However, their performance in practice is influenced by several factors, including side reactions at the anode, formation of unwanted by-products, and the intrinsic limitations of the oxygen reduction reaction (ORR) at the cathode [8], [9]. Furthermore, near-neutral and biocompatible environments such as artificial tear electrolytes exhibit electrochemical behavior that differs significantly from conventional alkaline or acidic systems. To date, only a limited number of studies have investigated cathode activity and ORR kinetics under such mild and biologically relevant conditions [4], [5]. The ORR process is one of the major rate-determining steps in metal–air batteries, and selecting an appropriate cathode material plays a central role in enhancing reaction kinetics. Gold, as a stable and biocompatible metal, has demonstrated favorable ORR activity at the nanoscale, and several works have improved its performance through dimension control, morphology engineering, or integration with conductive scaffolds [10], [11], [12]. In parallel, the use of light as an external stimulus to enhance electrochemical reactions has gained significant interest. Plasmonic structures based on gold can generate localized surface plasmon resonance under visible illumination, modifying local surface conditions and carrier density in a way that can accelerate ORR in certain systems [13]. Reports on photo-responsive batteries and illuminated electrochemical systems further suggest that visible light can enhance charge-transfer processes and improve the behavior of gold electrodes [14]. Nevertheless, light-induced enhancement in aluminum–air batteries operating in near-biological electrolytes especially using green laser excitation and gold cathodes has not yet been experimentally demonstrated in a systematic manner. In this work, we experimentally investigate the performance of an aluminum air cell employing a gold cathode in an artificial tear electrolyte under two operating conditions: without illumination and under 532-nm green laser excitation. To assess the influence of optical stimulation on cathodic behavior and charge-transfer processes, cyclic voltammetry (CV), galvanostatic discharge (GCD), and electrochemical impedance spectroscopy (EIS) measurements were conducted. The results show that laser illumination significantly enhances cathodic activity and overall cell performance, providing a basis for further development of biocompatible light-responsive energy systems for next-generation smart contact lenses and ocular sensors.

2. Experimental and methods

The aluminum–air cell used in this study was assembled using a 15-µm thick aluminum foil as the anode and a 30-nm gold film as the catalytic layer of the air cathode.

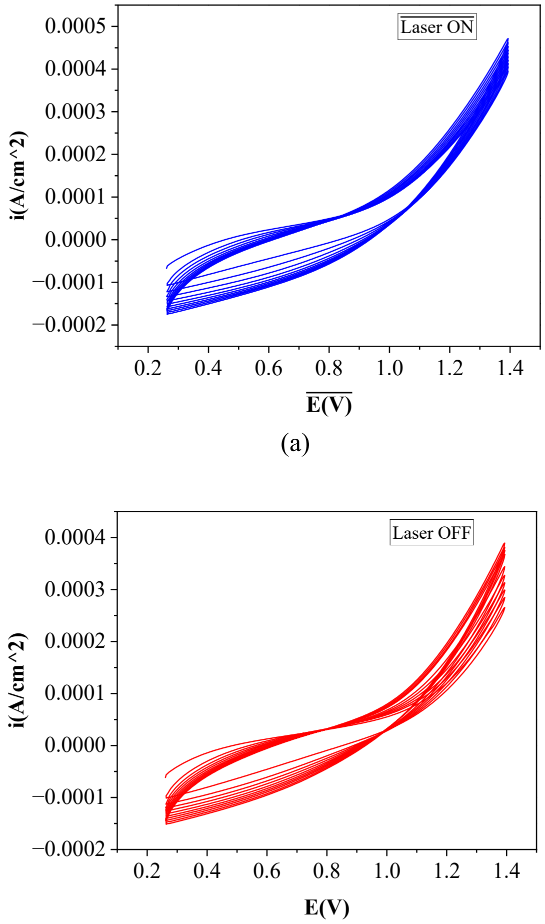
A 1.5-mm nickel foam was employed as the current collector, and a 1-mm PDMS (polydimethylsiloxane) membrane served as the gas-diffusion layer. The geometric area of both electrodes was fixed at 1 × 1 cm^2.Artificial tear solution was used as the electrolyte to ensure biocompatible operating conditions. To stimulate the oxygen reduction reaction (ORR), a 532-nm laser with a power of 25 mW was applied directly onto the surface of the gold catalytic layer. To evaluate the impact of laser irradiation on the electrochemical performance of an aluminum-air battery, a suite of three primary electrochemical tests, three primary electrochemical tests were carried out in both laser-on and laser-off states: cyclic voltammetry (CV), galvanostatic charge–discharge (GCD), and electrochemical impedance spectroscopy (EIS).

CV measurements were performed within a potential window of 0.2–1.4 V at a scan rate of 50 mV/s to assess changes in cathodic and anodic currents under illumination. GCD tests were performed at a constant current within the same voltage range (0.2–1.4 V) to evaluate discharge/charge capacity and discharge stability in the presence of the laser. For EIS, impedance spectra were recorded from 0.1 Hz to 100 kHz using a 10 mV AC perturbation to quantify variations in charge-transfer resistance and cathode interfacial behavior under optical excitation.

3. Results and discussions

Figure 1 presents the cyclic voltammetry curves of the aluminum–air cell under laser-illuminated (a) and dark (b) conditions.

A noticeable enhancement in the electrochemical response is observed when the cathode is exposed to 532 nm illumination. The cathodic peak current increases by approximately 18%, while the anodic peak rises by nearly 20% compared with the dark condition.



(a)

(b)

Figure 1. Cyclic voltammetry curves under (a) laser-on and (b) laser-off conditions

This simultaneous improvement in both reduction and oxidation peaks indicates that illumination accelerates the overall kinetics of the redox processes rather than selectively affecting only one half-cycle.

The integrated area of the CV curves representing the total charge exchanged during the cycle shows an increase of about 25% under illumination. This expansion suggests that a larger portion of the gold surface becomes electrochemically active, enabling more efficient charge-transfer processes. Such behavior aligns with the known optical response of gold in the green spectral region, where photo-excitation increases surface carrier density and lowers the activation energy of rate-limiting ORR steps.

Importantly, the overall shape and peak positions remain unchanged, confirming that illumination does not modify the dominant reaction pathway but enhances the kinetics along the same route.

Overall, the CV analysis demonstrates that 532 nm illumination significantly increases electrocatalytic activity, promotes easier charge transfer at the gold surface, and broadens the participation of active sites in redox processes.

Figure 2 displays the galvanostatic discharge profiles under illuminated (a) and dark (b) conditions.

The illuminated curve exhibits a smaller initial ohmic drop, indicating reduced interfacial and charge-transfer resistances. Such behavior reflects more favorable electrode–electrolyte contact and a more stable surface environment at the gold cathode during current operation.

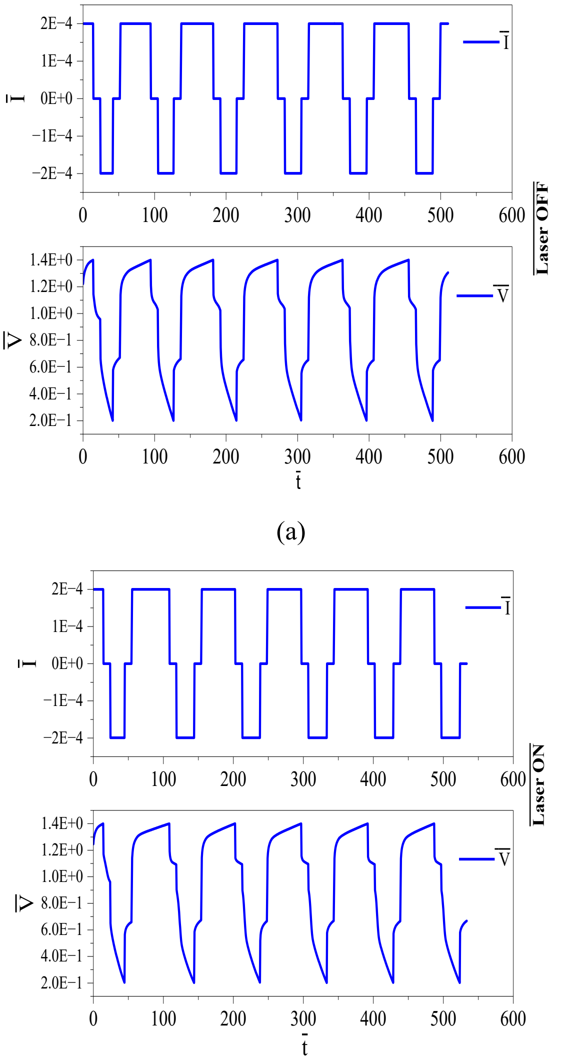
The discharge profiles under illumination demonstrate enhanced voltage trajectory stability, indicative of a more uniform and accelerated oxygen reduction reaction (ORR) kinetics. This observation suggests a diminished role for transport limitations within the reaction pathway.

A discernible increase of approximately 15% in specific discharge capacity correlates with heightened participation of active gold sites and improved catalytic efficiency.

Correspondingly, the specific energy increases by approximately 19%, consistent with a reduction in resistive losses and more efficient cathode surface utilization.

Improvements of approximately 7% in specific power and 5% in coulombic efficiency further suggest a greater contribution of the applied current towards the desired reaction pathway and a concomitant suppression of parasitic reactions.

Together, these observations confirm that illumination strengthens intrinsic reaction kinetics at the gold electrode and enhances the practical discharge behavior of the aluminum–air cell.

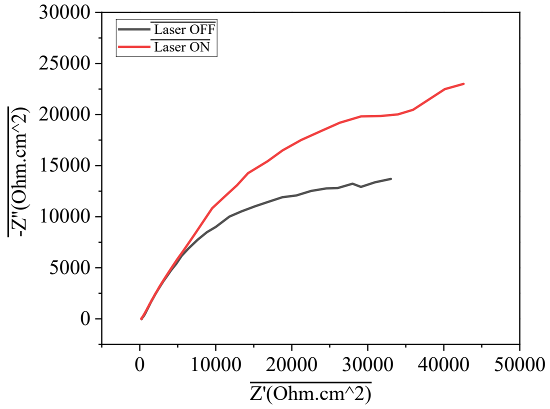


(a)

(b)

Figure 2. Galvanostatic charge–discharge curves under (a) laser-on and (b) laser-off conditions

Figure 3 presents the Nyquist plots of the aluminum–air cell under illuminated and dark conditions. A noticeable contrast emerges between the two states, revealing that 532 nm illumination influences the resistive components governing the electrochemical behavior of the system. Under illumination, the series resistance (Rs) decreases by about 20%, reflecting improved ionic transport and more favorable electrode–electrolyte interfacial conditions. The most pronounced change occurs in the cathodic charge-transfer resistance (Rct$_2$), which decreases by nearly 60% compared with the dark state.



(a)

Figure 3. Nyquist plots under laser-on and laser-off conditions

This substantial reduction demonstrates that optical excitation accelerates the kinetic steps of the oxygen reduction reaction at the gold cathode, enabling faster electron-transfer pathways. The high-frequency region shows similar behavior for both conditions, indicating that illumination primarily affects surface-controlled processes rather than altering electrolyte behavior or bulk ion-transport pathways. Overall, the EIS results show that 532 nm illumination creates more favorable electrochemical conditions by simultaneously reducing Rs and Rct$_2$. Combined with the improved CV and GCD responses, these findings provide consistent evidence that optical stimulation enhances both interfacial and kinetic aspects of the aluminum–air cell, highlighting the potential of light-assisted strategies for improving gold-based cathodes in biocompatible electrochemical systems.

4. Conclusion

This study investigates the performance enhancement of an aluminum-air battery equipped with a gold cathode under 532 nm laser irradiation. The electrochemical measurements reveal a significant influence of light exposure on the cathodic response and charge transfer kinetics. An increase of approximately 16% in the cathodic peak current, a nearly 13% enhancement in discharge capacity, and an around 60% reduction in charge-transfer resistance (Rct) collectively reflect a pronounced improvement in electrocatalytic activity under illumination. The enlarged CV area and the diminished initial voltage drop in the GCD curves further validate the consistency of these enhancements across independent techniques. Overall, these findings suggest that laser irradiation can effectively improve the cathodic performance and efficiency of aluminum-air batteries. The simplicity of the implementation and the readily available materials suggest a promising avenue for the development of future light-driven electrochemical power systems.

Disclosures

The authors declare no conflicts of interest.

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