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YST001 - ADVANCED NON-PLANAR ARCHITECTURE: NANOPOROUS ALUMINA (NPA) MILLIRODS

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ABSTRACT

Nanoporous alumina (NPA) millirods were developed in a milli-sized dimension by coaxially growing a highly ordered NPA layer on aluminum (Al) wire through a two-step electrochemical anodization. This non-planar architecture addresses the brittleness and limited active sites of conventional planar NPA membranes, producing mechanically robust and three-dimensional active sites for functionalization. The fabrication strategy, which involved polytetrafluoroethylene (PTFE) coatings and transverse cutting, produced multiple identical millirods from a single Al wire, ensuring reproducibility and cost-effectiveness. Growing the NPA to a rigid Al wire substrate provided NPA with solid physical support and ease of handling. These characteristics resulted in enhanced binding-site density, rapid mass transport, and direct electrical contact, making the NPA millirods ideal for high-sensitivity electrochemical sensing and various nanomaterial applications.

Keywords – Nanoporous alumina millirod, electrochemical anodization, aluminum wire, non-planar substrates

INTRODUCTION

Nanoporous alumina (NPA) has gained significant attention as a versatile material for functional nanomaterials, especially in applications requiring precise structural control and enhanced surface area. However, most NPA fabrication approaches focus on fabricating NPA as a bulk membrane on an aluminum (Al) foil with a perfectly planar geometry (Kovaleva et al., 2020; Sun et al., 2021). Despite its high prevalence in analytical applications as a nanomaterial platform, this planar NPA membrane has significant limitations, including brittleness, difficulties in miniaturization, and the provision of only one-dimensional active sites for functionalization (Huang et al., 2020). In this context, fabricating NPA on non-planar substrates (e.g., Al wire with a rod-like geometry) may offer new opportunities to overcome these limitations. Therefore, this project introduces NPA millirods with a milli-sized and rod-shaped architecture, fabricated from a single Al wire using a facile fabrication strategy. The motivation for developing NPA millirods is based on several prospects: (i) NPA growth on a single, non-planar Al wire is rarely reported, and remains poorly understood (Li et al., 2022), (ii) growing NPA on a single Al wire substrate as a rigid support provides the requisite mechanical strength to the resulting nanostructures; and (iii) the cylindrical architecture offers three-dimensional active sites with an enlarged surface area for further functionalization.

OBJECTIVE

The objective of this project is to develop a novel platform based on NPA millirods as an alternative to the conventional NPA platforms fabricated on Al foil substrates, which face challenges such as poor mechanical durability and limited potential for miniaturization. Specifically, the project aims to fabricate multiple individual NPA millirods from a single Al wire using a segmented fabrication strategy. The Al wire substrate will be partitioned using polytetrafluoroethylene (PTFE) tubing and then exposed to a two-step electrochemical anodization process to grow NPA on the uncoated segments. This will be followed by transverse cutting to produce individual NPA millirods.

DESCRIPTION OF THE PROJECT

This project describes the fabrication of NPA millirods in a milli-scale rod form (length: 5.0 mm, diameter: 1.0 mm) grown coaxially on Al wire via a two-step electrochemical anodization. This non-planar architecture offers mechanical robustness and a high surface area, providing a superior alternative to brittle planar NPA membranes. These features can increase the binding-site density and enhance analytical sensitivity. Partitioning the Al wire with PTFE tubing yields alternating NPA segments along a single Al wire. Transverse cutting then produces individual NPA millirods without surface damage, preserving the structural integrity required for reproducible and high-sensitivity applications. The fabrication process relies on inexpensive Al and standard laboratory reagents, making it both cost-effective and readily scalable. Therefore, these attributes position NPA millirods as a promising next-generation nanomaterial platform for electrochemical applications.

NOVELTY

The development of NPA millirods introduces a novel approach to nanomaterial fabrication using non-planar substrates. This innovative strategy enables the fabrication of multiple NPA millirods from a single Al wire with a rod-like geometry, representing a significant advancement over conventional planar NPA membranes. Using Al wire as the substrate provides promising physical support for nanoporous materials, enhancing flexibility in handling, and offering three-dimensional active sites with a larger surface area (Banerjee et al., 2014). To the best of our knowledge, non-planar NPA millirods with a rod-like geometry have not been explored as a nanomaterial platform, particularly in electrochemical applications. As illustrated in Figure 1, the facile fabrication strategy involving three main steps: (i) partitioning the Al wire into multiple segments using chemically inert polytetrafluoroethylene (PTFE) tubing, (ii) performing two-step electrochemical anodization at 80 V to coat each segment with a layer of NPA and (iii) cutting the Al wire transversely at each PTFE boundary to obtain multiple NPA millirods (length: 5.0 mm, diameter: 1.0 mm). This approach yields a novel NPA platform with a milli-sized, rod-shaped architecture that offers improved versatility and mechanical durability over conventional planar NPA membranes, making it highly suitable for electrochemical applications.

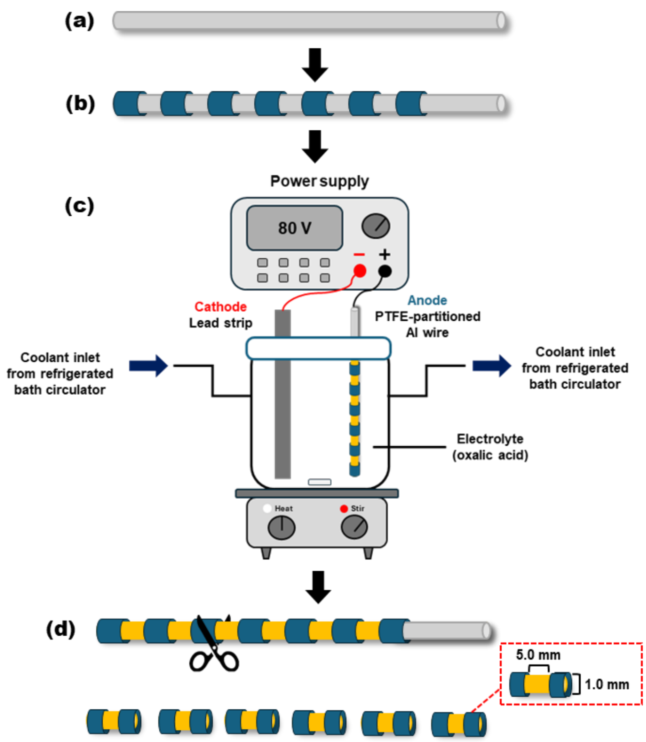

Figure 1: Schematic diagram of the fabrication of NPA millirods. (a) Bare Al wire with a rod-like geometry. (b) PTFE-partitioned Al wire. (c) Electrochemical anodization of Al wire. (d) Multiple individual NPA millirods.

CONCLUSION

This project successfully demonstrates a robust and cost-effective method for fabricating NPA millirods via a segmented anodization strategy. By enabling the simultaneous anodization of multiple regions along an Al wire in a single cycle, followed by transverse sectioning, this approach efficiently produces discrete NPA millirods with controlled size and geometry. It facilitates scalability and introduces an alternative NPA platform that overcomes the limitations of conventional planar substrates. The resulting NPA millirods exhibit improved mechanical durability, structural flexibility, and strong potential for integration into miniaturized electrochemical devices.

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