Revolution in the Fabrication of Topological Nanomaterials: A Versatile Approach via Thermomechanical Epitaxy

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Abstract: The accurate characterization and practical applications of topological materials demand nanostructures that enhances topological properties through amplified surface-to-volume ratios. While numerous topological materials have been proposed, their realization in nanomaterials has been significantly limited primarily by the constraints of current fabrication techniques. In this report, we introduce our versatile method, thermomechanical nanomolding (TMNM), for crafting general one-dimensional (1D) topological nanomaterials. Specifically, we subject a bulk feedstock material in a topological phase to compression against a robust nanoporous mold at an elevated temperature, yielding high-quality single crystalline topological nanowires through thermomechanical epitaxy. During this presentation, we will demonstrate the fabrication of various 1D topological nanomaterials, including topological insulators and topological semimetals. The underlying science behind nanowire growth and the precise control of nanowire geometry and dimensions will also be discussed.

Keywords: Nanofabrication, Thermomechanical Epitaxy, Topological Materials, 1D Nanomaterials, Diffusion.

1. Introduction

Topological materials, a recently discovered class of quantum materials known for their distinctive and split behaviors stemming from their unique electronic band structures, have captured substantial attention in the physics and materials science community over the past decade. The potential applications of one-dimensional (1D) topological nanomaterials in electronics and quantum computing have created a high demand for their fabrication techniques. The category of topological materials encompasses a broad range of chemical compositions and crystal structures [1]. However, realizing 1D topological nanomaterials remains a challenge due to the limited versatility of existing fabrication methods. Given the inherent presence of atomic diffusion in solids, our innovative approach, known as thermomechanical nanomolding (TMNM), offers a potentially universal solution for achieving general topological phases in nanostructures. In this method, a bulk feedstock material in a topological phase is compressed against a rigid free-standing nanoporous anodized aluminum oxide (AAO) mold at an elevated temperature, carefully controlled below the melting point of the topological phase. The applied pressure gradient drives the constituent atoms of the feedstock into the nanochannels of the mold through interfacial diffusion, resulting in epitaxial growth of high-quality single crystalline nanowires. To validate the reliability and versatility of our method, we selected a wide variety of topological materials that have been of significant interest in recent years. These materials include topological insulators and topological semimetals. We employed scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to meticulously examine the quality of the nanowires. This examination provided crucial insights into the chemical compositions, material phases, and crystallinity of the nanowires we aimed to achieve.

2. Technical Work

I. Feedstock Sample Preparation

Polycrystalline alloy samples were prepared through arc-melting. Subsequently, the samples were sliced into flat disc-like feedstocks and subjected to surface polishing in preparation for nanomolding.

II. Thermomechanical Nanomolding (TMNM)

Figure 1 provides an overview of TMNM process. To begin, prepared flat, disc-like feedstock samples were pressed against nanoporous anodic aluminum oxide (AAO) molds, which were sourced from InRedox. This pressing operation was conducted at a controlled pressure and processing temperature, consistently maintained below the melting points of the feedstocks. This process was carried out utilizing an Instron universal testing system equipped with heating plates. A controlled pressure was applied at a ramp rate of 20 MPa per minute. Once the desired pressure, ranging from 100 to 500 MPa, was achieved, it was held for a duration ranging from 10 minutes to 1 hour. Following the completion of the molding process, the AAO molds were selectively etched in a solution of 20 weight percent Potassium hydroxide or 10 weight percent phosphoric acid at room temperature for 10 hours. This process resulted in the creation of free-standing nanowire arrays.

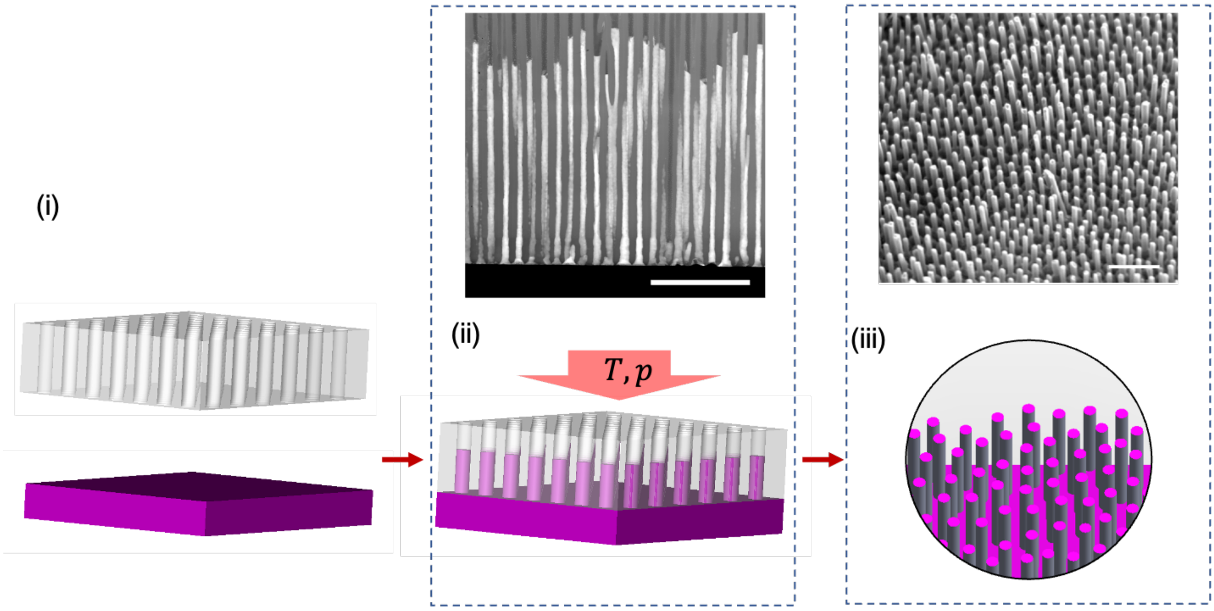

Fig. 1. Thermomechanical nanomolding (TMNM) process. (i) A free-standing nanoporous anodized aluminum oxide (AAO) mold and a flat alloy feedstock (typically measures 1 mm in thickness and 5 mm in width) are prepared. (ii) Subsequently, the mold is subjected to a pressure (p) ranging from 100 to 500 MPa, while maintaining a temperature (T) approximately at 0.5 times the melting point. A cross-sectional view of the nanowires filling the nanocavities of the mold is shown in the top (scale bar: 500 nm). (iii) Finally, the mold undergoes a chemical etching process, resulting in the removal of the mold. This leaves only the nanowire array behind (scale bar: 1 µm). [2]

3. Conclusions

This research highlights the profound impact of our approach in enabling the fabrication of 1D topological nanomaterials across a wide spectrum of chemical compositions, atomic crystal structures, and complexities, spanning elementary, binary, and ternary systems. These include materials that were previously challenging to fabricate into nanostructures using alternative methods. Furthermore, the exceptional quality of being single crystals with notably high aspect ratios (~100) is particularly exciting, given that applications and high-precision characterization of topological materials and states usually necessitate the attainment of single crystallinity, where grain boundaries and defects are eliminated to ensure topological functionality. This achievement represents a significant milestone with profound implications for the field of topological materials and beyond.

References

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