Lightweight Ultrastrong Thin-Shell Nanolattice Material for Enhanced Energy Dissipation

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Naturally occurring cellular materials like biological exoskeletons, bones, cork, and wood exhibit superior mechanical properties and are simultaneously lightweight. The material composition and the architectural arrangement of constituent elements in these materials at micro/nano scale results in improved strength and stiffness per weight. The elastic modulus for cellular solids are related to density through $E/E_s \propto \rho_R^n$, where E_s and E are elastic modulus for solid and cellular material, respectively, ρ_R is relative density, and n is scaling factor dependent on geometrical arrangement of components. For porous materials with random constituent elements, the material modulus scales poorly with density ($n \sim 3$). Recent research in the field of lightweight materials is focused on reducing the coupling between stiffness and yield strength with respect to density for favorable mechanical performance. It has been demonstrated that by having an ordered arrangement of constituent elements of the porous material, its properties can be improved to achieve robust mechanical performance [1-4]. However, the periods of existing lattice are in the ~10 μm range, which renders integration into material systems difficult.

Here we present a fabrication technique combining colloidal lithography with atomic layer deposition (ALD) to make ordered thin-shell porous nanostructure with lattice period in the 500 nm range. The fabrication process (Figure 1) begins with illumination of periodic array of nanospheres of diameter 500 nm with UV light source (λ = 325 nm). The resulting complex intensity pattern is recorded in the underlying positive-tone photoresist layer, yielding complex 3D periodic nanostructure [5] as shown in figure 1(a). The polymeric nanostructure is then conformally coated with alumina/ZnO using ALD process. Figure 1(b) shows a photoresist template coated with 40 nm alumina. The sample is then heated at 550°C for 30 minutes in a furnace to burn the photoresist template and get a free standing thin-shell tubular 3D porous nanostructure as shown in figure 1 (c).

The fabricated 3D porous nanostructures are tested for their mechanical characteristics using nanoindentation. A diamond probe with radius of 10 μm is used for nanoindentation and a cyclic incremental loading mechanism is used to measure mechanical response of samples. The unique arrangement of thin-shell tubular structures results in near-linear scaling between stiffness and density for both alumina and ZnO nanolattices, as shown in figure 2(c). The thinnest nanolattice material tested for mechanical properties with shell thickness of 4 nm of Al_2O_3 has stiffness 1.19 GPa, hardness 7.8 MPa, and energy dissipation per volume of 4.6 MJ/m^3 with porosity of 95.6%. The energy dissipation per volume is much larger than the previously reported ordered polymer nanoframes, even with smaller strain values and lower densities [1]. We will present a detailed report on nanoindentation testing methodology and also the analysis of effect of nanomaterial porosity on material properties like stiffness, hardness and energy dissipation per volume.

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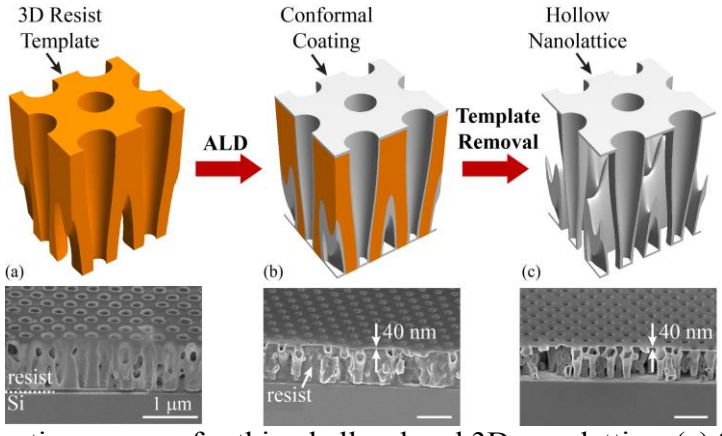

Figure 1. Fabrication process for thin-shell ordered 3D nanolattice. (a) Schematic of 3D photoresist template after colloidal lithography. SEM shows complex 3D structure after lithography. (b) Resist template coated with conformal 40 nm Alumina layer using ALD. (c) SEM image of free standing hollow 3D Alumina structure after burning the resist template.

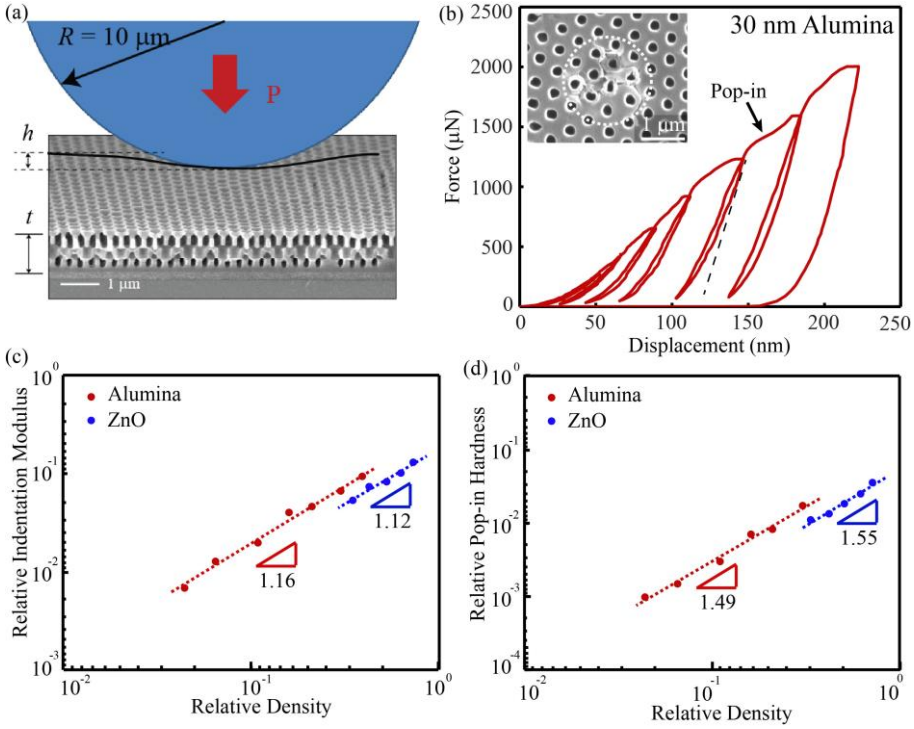

Figure 2. (a) Schematic of nanoindentation process for mechanical testing of thin-shell nanolattice. (b) Typical loading-unloading curve for incremental cyclic loading method. Pop-in indicates first instance of mechanical failure due to structure collapse. SEM showing the top view of structure collapse in 30 nm Alumina sample after nanoindentation (c) Stiffness scaling with respect to density (d) Hardness scaling with respect to density for Alumina and ZnO

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