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A Call to Action: Manufacturing Architected Materials

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Introduction: Architected materials continue to redefine the boundaries of materials science, opening up a wealth of new opportunities for innovation and economic growth. By creating entirely new classes of materials with custom tailored properties, researchers have created prototypes demonstrating promising outcomes that could impact the health, national security, energy independence, and economic prosperity of the nation. The United States has invested heavily in architected materials through a wide range of federal science and technology agencies, and developed world-leading experts, research facilities, and intellectual property. However, widespread application of architected materials is often limited by the manufacturability of the complex geometries used to realize their novel performance. Traditional manufacturing processes do not readily provide high-throughput solutions to manufacture critical features from the nanoscale to the macroscale or allow precise alignment of structural unit cells in three dimensions across large volumes. Realization of the true benefits of architected materials relies on translating research lab prototypes and processes to products and devices that can be manufactured at scale.

Recommendations: MForesight: Alliance for Manufacturing Foresight (MForesight.org) convened leading industry, research, and government experts to gather insights on the opportunities and challenges of manufacturing architected materials, and more broadly, metamaterials. The MForesight report, Manufacturing Metamaterials, highlights five actionable recommendations aimed at advancing U.S. manufacturing competitiveness in this space:

1. Establish a National Metamaterial Manufacturing Initiative (NMMI): a coordinated multi-agency federal research initiative focused on advancing metamaterial manufacturing to address critical barriers to commercial scale production. This includes scaling promising manufacturing processes relevant to metamaterials, developing manufacturing processes for multi-material systems, and developing metrology, simulation, and design tools for multi-scale, three-dimensional, and multi-material systems.

2. Ensure the availability, affordability, reliability, and quality of raw materials, substrates, and nanoparticles critical to metamaterials manufacturing. Government support of research and initial production, in conjunction with enhanced standards, certifications, and benchmarks will help ensure the availability of quality feedstock.

3. Increase access to existing federal facilities and expertise associated with advanced manufacturing methods, characterization tools, design codes, and computing power.

4. Create a National Center of Excellence to serve as a focal point and driving force for ensuring effective industry participation, fostering shared research efforts, developing and adapting manufacturing equipment, creating workforce training programs, test-piloting production, and facilitating prototype production.

5. Establish an interdisciplinary working group comprising researchers, equipment vendors, program managers, and metamaterials producers and users to provide real-time input towards manufacturing technology road-mapping, research priorities, standards, intellectual property, and other issues to ensure accelerated progress.

Technical Focus: The MForesight report highlights a range of technologies worth scaling and challenges in need of additional attention. Specifically, emerging process technologies showing promise for scalable metamaterials manufacturing include nanoimprint lithography (NIL), pattern transfer, additive manufacturing, and bottom-up approaches. Essential research topics for NIL include advancing thermal and ultraviolet-assisted approaches, metallizing patterned surfaces, application of NIL features as etch masks, and broadening the set of NIL compatible materials. Pattern transfer processes need improvements in layer alignment and residual strain compensation and mitigation. In additive manufacturing, opportunities for metamaterials manufacturing include multi-nozzle arrays, self-propagating feature guides, and massively parallel sintering. Bottom-up fabrication methods, such as DNA-based assembly, block co-polymer templating, and self-assembly offer the promise of

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direct 3D fabrication, yet additional attention is needed to enable these technologies, including size agnostic processes, guided assembly, and models for self-assembly processes and disorder. Leveraging the periodic nature of metamaterials will greatly benefit these manufacturing processes, with research needed in self-aligning technologies, combining repetition with variation, adapting semiconductor step and repeat technologies, and rapid, real-time sensing and adjustment.

Manufacturing architectures containing multiple materials necessitates research on disparate materials joining, developing materials conducive to joining, and creating novel multi-material and material agnostic processes. Simulation and design tools that underlie development through scaled production require advancements in computational tools for manufacturability, periodic structures, and 3D multi-scale multi-material structures. These are complimented by advancement of manufacturing sensitive analysis methods, process technology models, and high performance computing codes.

Funding of translational materials research should focus on environmentally robust nano-particles, novel plasmonic materials, scalable nano-manufacturing processes, and enhanced materials for active metamaterials (e.g. varactors, phase change, etc.). Substrate advancements include manufacturing methods for large-format and curved substrates, nanoscale selective epitaxial growth and dopant patterning, extending traditional processes (e.g. immersion-based optical lithography, loose abrasive processes, etc.), and fabrication of substrates with non-traditional materials, doping, and coatings.

Conclusion: As a rapidly expanding opportunity with cross-cutting applicability, rapid, coordinated action by stakeholders will help ensure U.S. investment in metamaterials translates to platforms for economic growth and technical leadership. While there are acute barriers restraining architected materials from reaching their commercial potential, these barriers are not insurmountable and with focused federal and private action, the vision of ubiquitous manufacturing and utilization of these novel materials is achievable.

For an extended report of findings, recommendations, and contributors [1] please visit MForesight.org.

1. Spadaccini, C. & Bishop-Moser, J. (2018). *Metamaterials Manufacturing*. Ann Arbor, MI: MForesight: Alliance for Manufacturing Foresight.

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