Warp-knitted glass fiber architectures for chip-scale electromagnetic-thermal-mechanical integration

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The rapid development of artificial intelligence, high-performance computing, and heterogeneous integration has pushed modern electronic systems beyond the limits of transistor scaling, making performance increasingly constrained by coupled thermal, electromagnetic, and mechanical effects. In advanced architectures, power densities can exceed hundreds of W/cm^2, leading to strong heat accumulation and local thermal runaway that degrades both performance and device lifetime.[1] Meanwhile, high-speed electronic devices are operating over an ever-wider frequency spectrum ranging from GHz bands to millimeter-wave windows. Against such dual trends, packaging layers within shrinking device volumes are required to simultaneously address challenges such as concentrated heat dissipation and thermomechanical stress issues.

On the other hand, the coexistence of materials, including silicon, copper, and low-*k* dielectrics, generates severe thermo-mechanical mismatch, where repeated thermal cycling accumulates interfacial stress and triggers delamination and reliability failure (Figure 1). Although thermal interface materials and electromagnetic shielding layers have been widely developed, they are typically optimized independently. For example, thermal media prioritize phonon transport, electromagnetic layers focus on conductivity or magnetic loss, and mechanical components mainly provide stress relief. As a result, there is a clear need for architected material systems that integrate thermal, electromagnetic, and mechanical functions within a unified framework.

WHY WARP-KNITTED GLASS FIBER ARCHITECTURES

Architected fibrous materials provide a promising pathway toward unified multifunctional chip packaging systems by enabling the co-design of mechanical support and coupled field regulation within a single structural framework. Among these, warp-knitted glass fiber architectures remain comparatively underexplored, despite offering a distinctive combination of structural robustness and functional integration potential. Warp-knitted architectures occupy an intermediate and highly programmable regime, where stitch topology, yarn orientation, and local density can be independently tailored to regulate mechanical compliance and directional thermal or electromagnetic transport. This topological freedom is particularly attractive for chip packaging, where multiple functional pathways must coexist within a thin and mechanically tolerant framework.

Beyond mechanical advantages, the defining strength of warp-knitted architectures lies in their hierarchical and programmable topology. The loop-based knitting network can be systematically engineered across multiple length scales, enabling precise control over structural anisotropy and internal connectivity. By adjusting yarn orientation and knitting patterns, warp-knitted glass fiber fabrics can be configured into biaxial, triaxial, or quadraxial architectures, allowing independent tuning of stiffness, thermal conductivity pathways, and electromagnetic response. Straight, closely arranged load-bearing yarns deliver superior directional thermal and electrical conduction. Whereas loop-rich and more open architectures increase compliance, inter-yarn contact density, and multiple-scattering pathways. Consequently, tricot-, raschel-, or other warp-knit-derived topologies can in principle be translated into different effective thermal-conductivity, electromagnetic-permittivity/permeability, and mechanical-stiffness tensors. This multiaxial design capability is particularly relevant for chip-scale integration, where heat dissipation, current transport, and stress distribution must be simultaneously optimized yet decoupled in their directional control.

In addition, the inherent porosity and interconnected void network of warp-knitted structures provide a highly accessible framework for multi-phase functionalization. These architectures can accommodate a wide range of secondary phases, including ceramic fillers, metallic nanoparticles, carbon-based nanostructures, and polymer matrices, enabling the construction of hierarchical composites in which structural and functional components are integrated at multiple scales. Rather than serving as passive reinforcement, the fibrous scaffold becomes an active template for organizing functional matter and guiding transport processes.

PROGRAMMABLE MULTIFUNCTIONAL ARCHITECTURES

Beyond structural reinforcement, the functional value of warp-knitted glass fiber systems arises from their ability to host and organize multiple coupled physical fields within a single fibrous scaffold. By deliberately introducing thermal, electromagnetic, and magnetic functionalities into the textile architecture, these systems transition from passive load-bearing media to programmable multiphysics platforms capable of actively regulating energy, signal, and stress transport. Because pristine glass fibers exhibit intrinsically low thermal conductivity, efficient heat management depends on constructing continuous and directional thermal pathways within the porous network. This is typically achieved by incorporating high-conductivity fillers such as hexagonal boron nitride, aluminum nitride, alumina, or graphene-based materials.[2] When these anisotropic fillers are guided along fiber axes or confined within inter-fiber channels, they assemble into percolative heat-conduction networks that support directional thermal transport. Such an architecture enables spatial control of heat spreading, allowing thermal gradients to be redistributed and localized hotspots in high-power-density electronic systems to be effectively suppressed.

Electromagnetic functionality emerges from the cooperative interaction between conductive and magnetic loss components embedded within the fibrous framework. Conductive nanomaterials such as carbon nanotubes, graphene sheets, and MXene nanosheets form interconnected networks that enhance reflection, conduction loss, and interfacial polarization.[3] In parallel, magnetic nanoparticles including Fe_3O_4, MnZn ferrites, and NiZn ferrites introduce multiple dissipation channels, including natural resonance, exchange resonance, and domain-wall relaxation. Unlike conventional planar shielding layers dominated by surface reflection, warp-knitted architectures provide a three-dimensional transport network that promotes repeated scattering and volumetric attenuation, resulting in enhanced absorption-dominated electromagnetic shielding performance.

Magnetic functionalization further expands the capability of warp-knitted glass fiber systems by introducing tunable permeability and frequency-dependent energy dissipation. Such behavior is particularly attractive for emerging high-frequency communication technologies and signal-integrity-sensitive electronics, where suppression of electromagnetic noise and mitigation of parasitic coupling become increasingly important. In addition, the combination of conductive and magnetic phases enables complementary attenuation mechanisms, extending electromagnetic shielding from simple reflection-dominated behavior toward broadband absorption and energy dissipation. Future magnetic functionalization should be benchmarked using frequency-resolved shielding effectiveness and absorption/reflection partitioning rather than a single shielding value. Engineering μ' and μ'' through ferrite or metallic magnetic fillers, together with conductive pathways and geometric resonances, may enable absorption-dominant attenuation over targeted GHz or mm Wave bands. The resulting bandwidth and attenuation must ultimately be evaluated against commercial shielding films at comparable thickness and areal density.

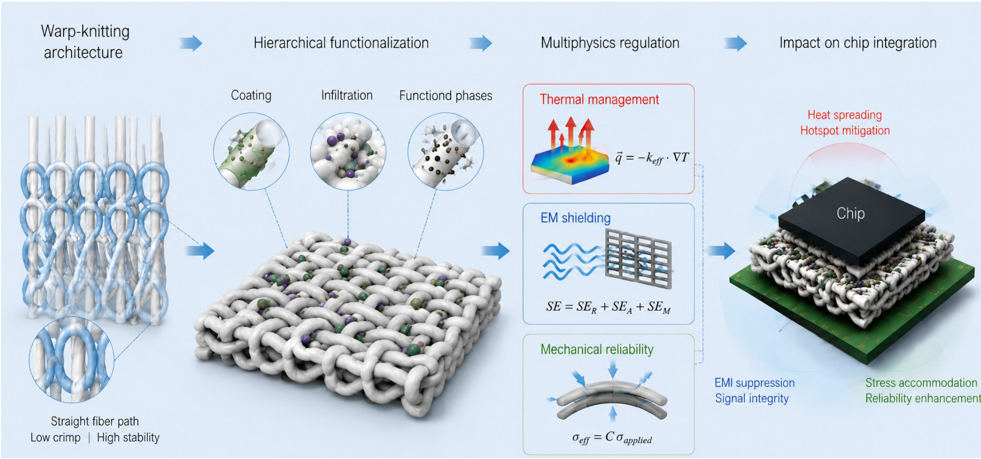

Figure 1. Schematic illustration of warp-knitted glass fiber architectures for chip-scale multi-physics integration.

The most distinctive feature of warp-knitted architectures is that thermal transport, electromagnetic attenuation, magnetic dissipation, and mechanical support are integrated within the same structural network.[4] Ceramic or carbon-based fillers establish heat-conduction pathways. Conductive and magnetic phases regulate electromagnetic propagation. The glass-fiber framework maintains structural integrity and accommodates thermomechanical stress. Because these functions share a common architecture, changes in one physical process inevitably influence the others, creating opportunities for coordinated regulation rather than isolated optimization. This architectural approach differs fundamentally from conventional multilayer packaging strategies, where thermal, electromagnetic, and mechanical functions are often addressed independently. As a result, warp-knitted glass fiber systems can be viewed as multifunctional platforms in which structural design governs the transport and dissipation of energy, signals, and stress across multiple length scales.

WARP-KNITTED FIBERS FOR FUTURE CHIP INTEGRATION

The continued development of electronics toward embodied intelligence, neuromorphic computing, and ultra-low-power architectures will require a transition from conventional passive packaging toward adaptive, functionally responsive systems. In these emerging platforms, thermal, electromagnetic, and mechanical fields will no longer be treated as independent constraints but must be dynamically regulated in response to spatial and temporal variations in device operation.

Within this framework, warp-knitted glass fiber architectures provide a structurally scalable pathway toward adaptive packaging layers with built-in multiscale responsiveness. Their hierarchical fibrous networks can be engineered not only as mechanical reinforcements but also as carriers of distributed sensing and stimulus-responsive functionalities. This enables packaging layers to evolve from passive isolation barriers into active regulatory components capable of participating in feedback-driven system-level optimization.

Beyond classical electronic systems, magnetically functionalized warp-knitted architectures offer additional opportunities for spintronic and quantum device integration, where the preservation of spin coherence and suppression of decoherence processes are central challenges.[5] For spintronic or quantum-device environments, the relevance of such architectures lies in mitigating external perturbations that can contribute to coherence degradation. Directional heat-spreading networks may reduce local temperature fluctuations. Conductive and magnetic-loss pathways can attenuate electromagnetic interference over selected frequency windows. The mechanically compliant interconnected loops may dissipate externally transmitted vibration. Therefore, their co-integration within a single scaffold could reduce simultaneous thermal, electromagnetic, and mechanical noise delivered to sensitive device regions.

From a practical manufacturing perspective, the intrinsic compatibility of glass fiber-based architectures with mature textile engineering and composite processing techniques ensures strong scalability. Processes such as warp knitting, resin infiltration, coating, and functional particle impregnation can be directly integrated into existing industrial production lines, thus reducing the barrier between laboratory-scale material design and semiconductor packaging implementation. This compatibility is particularly important for large-area packaging and heterogeneous integration platforms. Scaling such multifunctional textiles also requires control over nanoparticle infiltration and interfacial quality. Nonuniform penetration of conductive or magnetic fillers can create spatially discontinuous transport networks, whereas weak adhesion at glass-fiber/functional-phase interfaces and residual voids may increase both electrical and thermal contact resistance. Surface functionalization, low-viscosity or vacuum-assisted infiltration, electrophoretic deposition, and conformal coating approaches may improve filler uniformity and interfacial coupling. Process development must additionally consider dimensional and interfacial stability during solder-reflow, curing, and thermal-cycling conditions.

In summary, warp-knitted glass fiber architectures represent a scalable class of structural-functional materials capable of addressing the coupled thermal, electromagnetic, and mechanical challenges. Future research should focus on establishing quantitative structure-property relationships. Establishing quantitative topology–property relationships will require combining direction-resolved thermal-conductivity measurements, vector-network-analyzer-based electromagnetic characterization and vibration testing, and three-dimensional structural imaging with representative-volume-element. Such approaches could map stitch geometry, yarn density, filler distribution, and interfacial resistance onto effective transport and mechanical tensors.

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DECLARATION OF INTERESTS

The authors declare no competing interests.