This article has been accepted for publication in IEEE Transactions on Components, Packaging and Manufacturing Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TCPMT.2025.3603484

Material Needs and Measurement Challenges for Advanced Semiconductor Packaging: Understanding the Soft Side of Science

Ran Tao, *Member, IEEE*, Polette Centellas, Stian Romberg, Anthony Kotula, Gale Holmes, Amanda Forster, Christopher Soles, Robert Allen, Edvin Cetegen, William Chen, *Life Fellow, IEEE*, Jeffrey Gotro, *Senior Member, IEEE*, and Mark Poliks, *Senior Member, IEEE*

***Abstract*—This *Perspective* builds upon insights from the National Institute of Standards and Technology (NIST)-organized workshop, "Materials and Metrology Needs for Advanced Semiconductor Packaging Strategies," held at the 35th annual Electronics Packaging Symposium in Binghamton, NY, on September 5, 2024. It outlines critical challenges and opportunities related to polymer-based "soft" materials in advanced semiconductor packaging, with emphasis on polymer science, measurement science (metrology), and the strategic development of Research-Grade Test Materials (RGTMs). These efforts, led by the NIST CHIPS team, aim to advance the fundamental understanding of structure–property–processing relationships, promote standardized guidelines and innovative methods for material characterization, and accelerate the development, qualification, and adoption of next-generation packaging materials. The *Perspective* also distills key insights from the panel discussion with industry experts, emphasizing the need for close collaboration among materials scientists, process engineers, and metrology experts to enable a holistic strategy, further highlighting the importance of cross-sector partnerships among industry, academia, and government to address pressing challenges in packaging materials and processes.**

***Index Terms*— Advanced semiconductor packaging, cure kinetics, heterogeneous integration (HI), metrology, moisture reliability, open access, open data, polymeric materials, residual stress, research-grade test materials (RGTMs), standardization and reproducibility, structure-property relationships, thermoset resins, underfill materials, viscoelastic modeling, warpage.**

I. INTRODUCTION

POLYMERIC materials—soft, versatile compounds composed of long, flexible, and repeating molecular chains—have been used in semiconductor packaging for decades. Since the early 1960s, polymeric packaging materials have primarily served a straightforward function: mechanically encapsulating chips and securely attaching them to circuit boards [1]. Historically, polymer-related challenges, such as coefficient of thermal expansion (CTE) mismatch and moisture absorption (the so-called "popcorning" effect [2]), were primarily associated with mechanical reliability concerns rather than directly affecting device performance. Many of the polymeric materials introduced decades ago, including epoxies, silicones, and polyimides, remain remarkably similar to those still widely used today. They continue to fulfill critical roles such as encapsulants, underfills, molding compounds, adhesives, thermal interface materials (TIMs), and substrate dielectric layers (**Fig. 1**), providing essential electrical insulation, mechanical support, and environmental protection for advanced packages [3, 4].

Today, the semiconductor industry is undergoing a transformative shift towards heterogeneous integration (HI) [5] to overcome the limitations of traditional transistor scaling and achieve enhanced performance, miniaturization, and cost efficiency. Over the next decade, emerging technologies—including 5G/6G wireless networks, artificial intelligence (AI), and high-performance computing (HPC), will rely heavily on advanced packaging enabled by HI [6]. As packaging architectures evolve into increasingly intricate 3D structures with finer feature sizes, smaller gap heights, flexible chiplets, and diverse materials interfaces, the demands on polymeric materials have become significantly more stringent. A broad spectrum of properties—including mechanical, thermal, electrical, and chemical—must now be simultaneously optimized. For instance, the transition from rigid chips to flexible electronic systems demands polymers with enhanced flexibility, toughness, and long-term fatigue resistance [7]. Likewise, 5G/6G applications require precise

This work was supported in part by the National Institute of Standards and Technology, U.S. Department of Commerce, under Award # 70NANB24H283. It was performed with funding from the CHIPS Metrology Program under Project 3.01, "Accurate Cure Kinetics, Stress, Mechanical Properties, and Warpage Measurements for Next-Generation Microelectronics Packaging under Device-Relevant Conditions," as part of CHIPS for America, National Institute of Standards and Technology, U.S. Department of Commerce. *(Corresponding author: Ran Tao).*

Ran Tao, Polette Centellas, Stian Romberg, Anthony Kotula, Gale Holmes, Amanda Forster, and Christopher Soles are with National Institute of Standards and Technology, Gaithersburg, MD 20899 USA (e-mail: ran.tao@nist.gov).

Ran Tao is also affiliated with North Carolina State University, Raleigh, NC 27695 USA.

Robert Allen is with National Renewable Energy Laboratory, Golden, CO 80401 USA.

Edvin Cetegen is with Intel Corporation, Chandler, AZ 85226 USA

William Chen is with Advanced Semiconductor Engineering, Inc., Sunnyvale, CA 94085 USA

Jeffrey Gotro is with Innocentrix, LLC, Rancho Santa Margarita, CA 92688 USA

Mark Poliks is with Binghamton University, Binghamton, NY 13902 USA.

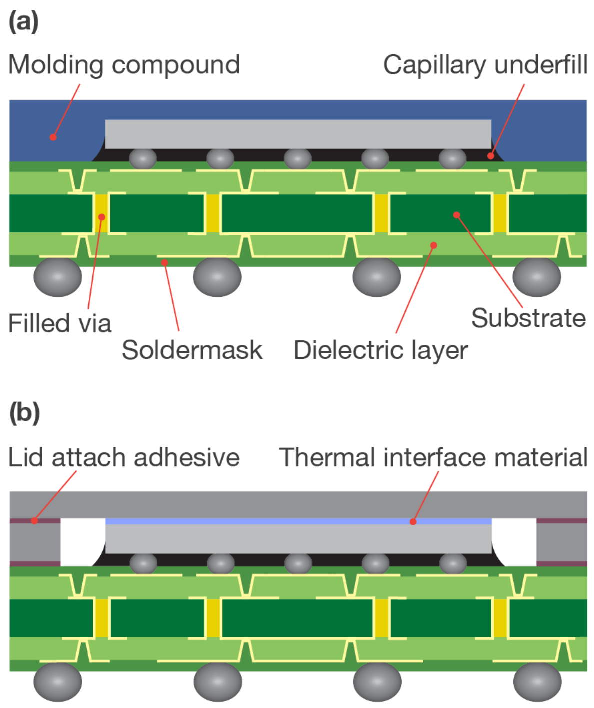

Fig. 1. Polymer-based materials used in advanced packaging. (a) An overmolded flip chip package. (b) A lidded flip chip package.

control over dielectric properties to minimize transmission loss and maintain signal integrity in high-frequency operating environments [8, 9]. Furthermore, integrating a wide range of materials into complex 3D multi-chip structures presents significant challenges in materials selection, process optimization, and interconnect reliability [10].

These evolving requirements underscore the need to re-examine legacy packaging resins and develop high-performance polymer-based materials tailored for next-generation technologies [11]. Modern formulations often involve multiple resins, multifunctional additives, and inorganic fillers, significantly increasing the complexity of material design and manufacturing. This is further compounded by the industry's heavy reliance on overseas material suppliers [12], limited transparency into material composition and performance data, and inadequate characterization standards and metrology methods, all of which create additional hurdles in materials development and implementation. At the same time, longstanding challenges—such as thermomechanical reliability concerns intrinsic to polymer behavior—persist and are further amplified in the context of HI.

Addressing these multifaceted challenges requires a robust and integrated materials science framework underpinned by advanced and precise metrology techniques [13]. This *Perspective* explores key challenges and opportunities related to polymer-based materials in advanced semiconductor packaging, with a focus on polymer science fundamentals, measurement science (metrology), and the strategic implementation of Research-Grade Test Materials (RGTMs). These components are essential for deepening the fundamental understanding of structure-property-processing relationships in complex polymer formulations, promoting standardized guidelines and innovative methods for material characterization, and accelerating the development, qualification, and adoption of next-generation packaging materials.

II. POLYMER-BASED MATERIALS IN ADVANCED PACKAGING

Given the diverse roles and growing functional demands of polymer-based materials in advanced packaging applications, careful optimization of their chemical composition, mechanical properties, thermal stability, and dielectric performance is essential. In this section, we briefly revisit key principles in polymer science—spanning both polymer physics and chemistry—that lay the groundwork for understanding structure-property-processing relationships in these materials.

The glass transition temperature (T_g) is often reported as a single value in material datasheets—but the underlying physics is far more complex and intriguing [14]. As Nobel Laureate P. W. Anderson famously remarked, the glass transition is "perhaps the deepest and most interesting unsolved problem in solid-state physics [15]." T_g marks the temperature range over which a crosslinked polymer gradually transitions from a rigid, glassy state to a soft, rubbery state, dictating the material's physical and mechanical properties, processing conditions, and application temperature limits [16].

However, the glass transition as measured in the laboratory is not a thermodynamically defined phase change; rather, it is a kinetic phenomenon that arises from the dramatic slowdown of molecular motions as the material cools and falls out of equilibrium [14, 16, 17]. As such, T_g depends on the intrinsic polymer structure as well as external factors such as *timescale* (rate or frequency), *thermal history* (how the glass is formed), and *measurement method* (i.e., the property being probed). The value of T_g increases by approximately (3 to 5) °C for every order-of-magnitude increase in cooling rate [17, 18]. Furthermore, T_g can shift under real-world operating environments—through mechanisms such as physical aging [19], stress relaxation, and moisture ingress, which alter the polymer relaxation dynamics and effectively modify its glass transition behavior.

The glass transition has many manifestations, including changes in heat capacity, specific volume, modulus, viscosity, and dielectric constant. Each manifestation is measured by a different technique. Thus, in practice, T_g can vary significantly depending on how it is measured— differential scanning calorimetry (DSC), dynamic mechanical analysis (DMA), rheometry, thermomechanical analysis (TMA), dilatometry, or dielectric analysis (DEA) each detect different property changes [20]. For example, T_g values from DMA loss tangent peaks can be (15 to 20) °C higher than those measured by dilatometry on cooling at 1 °C/min—a discrepancy that can lead to substantial error when predicting rate-dependent processes [21]. Even within a single method

This article has been accepted for publication in IEEE Transactions on Components, Packaging and Manufacturing Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TCPMT.2025.3603484

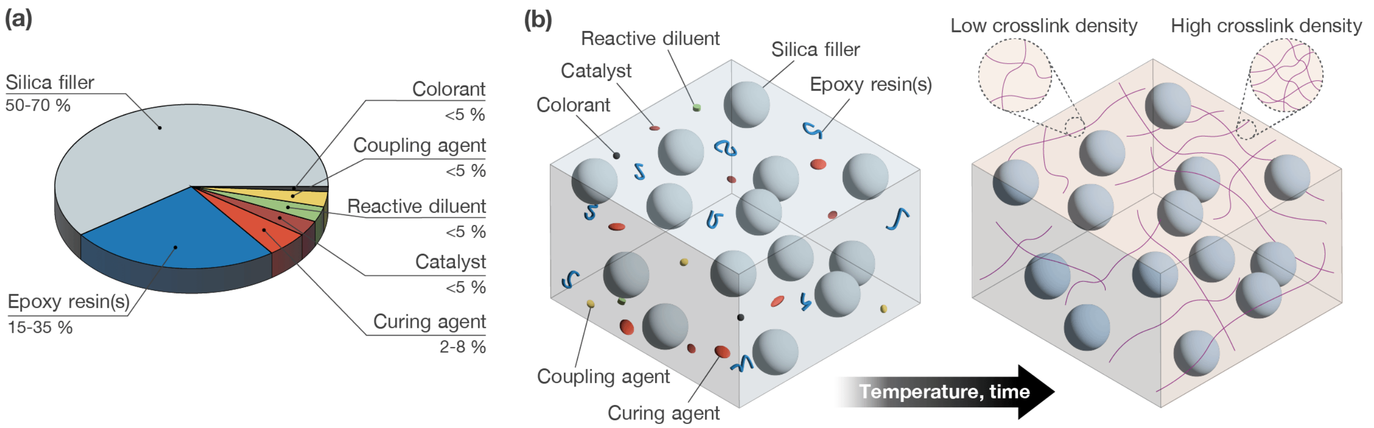

Fig. 2. **(a)** Typical composition of an epoxy-based underfill material shown as a pie chart; **(b)** Molecular-level schematic of the formulation highlighting the dispersion of functional additives and fillers within the epoxy matrix. Upon thermal curing, the epoxy resins undergo crosslinking reactions to form a three-dimensional polymer network.

like DSC, T_g may be reported using different criteria for the midpoint of the heat capacity step change, such as the inflection point, half-height, or fictive temperature. This is simply because the transition occurs over a temperature range rather than as a sharp, single point. Therefore, reporting T_g without specifying the measurement technique and analysis method is inadequate for meaningful interlaboratory comparisons.

Advanced formulations for polymer-based packaging materials are highly complex, often incorporating significant amounts of inorganic fillers along with a variety of additives to meet performance requirements (**Fig. 2a**). In thermoset polymers, which constitute the majority of polymer-based packaging materials, the curing process typically occurs through thermal crosslinking—a chemical reaction at elevated temperatures in which resin molecules polymerize into longer chains and eventually link together to form a rigid, three-dimensional network (**Fig. 2b**). As curing progresses, T_g increases from the initial value of the uncured monomer mixture (T_{g0}) to the fully cured value ($T_{g\infty}$).

The ability to control crosslink density and polymer network structure through tailored polymer chemistry is central to designing base resins that define the basic physical and mechanical properties of the material. In epoxy-based formulations—a nearly century-old chemistry—the choice of monomers, curing agents, and catalysts, along with their stoichiometry and reactivity, directly influences reaction kinetics and the architecture of the resulting polymer network [22]. Factors such as mono- vs. multi-functional epoxides, aliphatic vs. aromatic curing agents, type of curing agent (e.g. anhydride, amine, or Lewis acid), or the use of reactive diluents and modifiers can significantly impact the rate of polymerization (cure kinetics), gelation time, and the onset of vitrification, ultimately affecting storage life, the processing window, and final material properties [23]. Additionally, insufficient mixing of reactants prior to the gel point could result in network and morphological inhomogeneities [22], such as regions of low versus high crosslink density, as shown in **Fig. 2b**.

Fillers add yet another layer of complexity to the resin systems. Optimizing filler content, surface chemistry, and particle size and distribution is crucial to balance performance with manufacturability [24]. For example, in capillary underfill formulations, low viscosity is required for efficient dispensing (**Fig. 3a**), while high filler loading is necessary to reduce CTE. However, increasing filler content typically raises viscosity and complicates flow behavior [25], introducing effects such as thixotropy—a reversible, time-dependent decrease in viscosity under shear—and yield stress, both of which can adversely impact processability [26, 27]. This interplay between filler-resin interactions and the evolving polymer network during curing highlights the need for accurate chemoviscosity models, which describe how viscosity changes with the degree of cure, time, and temperature [28]. In practice, underfills are frequently dispensed at elevated temperatures to reduce viscosity, accelerate the process, and minimize the presence of voids in the cured underfill. Similarly, for advanced molding compounds used in compression molding of fan-out wafer/panel-level packaging (FO-WLP/FO-PLP), accurate prediction of material behavior during curing (chemorheology) is essential for effective warpage management [29, 30]. Process-induced warpage—arising from CTE mismatch between different components, cure shrinkage, and hygrothermal stressors (**Fig. 3b**)—can lead to significant reliability risks, such as die shift, interconnect misalignment, and interfacial delamination [31]. The mechanical behavior, adhesion, and stress-related performance of polymeric composites are critically important in this context, as they directly affect warpage control, stress reduction, and interfacial reliability in the final package. Addressing these challenges requires an integrated approach that combines advanced materials design, predictive modeling, and process control [32, 33].

This article has been accepted for publication in IEEE Transactions on Components, Packaging and Manufacturing Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TCPMT.2025.3603484

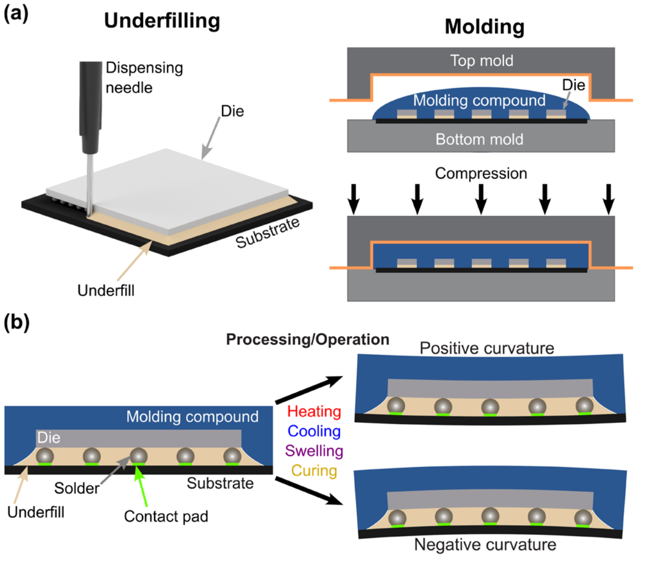

Fig. 3. (a) Underfilling and molding steps used to encapsulate and protect chips. **(b)** Schematic cross-sections depicting how processing conditions can induce warpage.

III. INTRINSIC CHALLENGES BY POLYMERIC MATERIALS IN ADVANCED PACKAGES

Despite their versatility and cost efficiency, polymeric materials inherently present challenges in semiconductor packaging due to their *cure-dependent*, *temperature-sensitive*, *hygroscopic*, and *viscoelastic* (time-dependent) behaviors. In this section, we highlight several important practices and insights from polymer research that help inform material processing strategies.

A. Accurate Cure Kinetics for Advanced Resin Formulations

Understanding cure kinetics and designing optimized curing schedules are essential for achieving desired material performance and improving manufacturing productivity. Advanced resin formulations with highly loaded fillers often exhibit complex, multi-step reactions that pose challenges for both measurement [34] and kinetics modeling [35-37]. Recent advances in kinetic analysis software have enabled the extraction of kinetic parameters from thermal analysis data that account for both chemical and diffusion-controlled kinetics [38]. Accurate cure kinetics models enable predictions and simulations under varying processing conditions (time and temperature), improve on-tool efficiency (e.g., post-mold cure design), and help reduce energy costs. These models are also foundational for enabling predictive modeling of process-dependent properties such as chemoviscosity and chemorheology [39, 40]. As noted earlier, T_g is a sensitive indicator of the degree of cure [41]—especially during the final stages where, for example, a 1% increase in conversion between 90 % and 100 % was observed to raise T_g by about 5 °C in an epoxy system [42, 43]. Therefore, establishing the T_g vs. conversion relationship is imperative when optimizing the cure profiles.

B. Process Pathways Influence Residual Stress Development

Residual stress remains a longstanding challenge in composites manufacturing. Effective process optimization requires careful stress management throughout every stage of production. The buildup of residual stress is highly dependent on the processing pathway [44, 45], specifically, the temperature and time profile the material experiences to reach its final degree of cure. Therefore, optimizing cure schedules requires a deep understanding of the material's transformation behavior during processing.

The Time-Temperature-Transformation (TTT) diagram provides a conceptual framework for understanding the key transitions during the isothermal curing of a thermoset [46, 47]. **Fig. 4** highlights two key critical transitions that influence manufacturability and residual stress development: gelation and vitrification.

Gelation (red curve) marks the onset of a space-spanning, infinite molecular network [48], characterized by an exponential increase in viscosity that theoretically diverges at the gel point and coincides with the initial emergence of an equilibrium elastic modulus [49, 50]. Beyond this point, the material loses its ability to flow, significantly impacting processability (e.g., dispensing and molding). Critically, after gelation, process-induced stress begins to accumulate as the material transitions from a viscous liquid to a gel-like, viscoelastic solid. *Vitrification* (S-shaped blue curve) occurs when the T_g of the material exceeds the cure temperature (T_c) [46]. As discussed earlier, T_g rises from the initial uncured T_{g0} towards the ultimate $T_{g\infty}$ as crosslinking proceeds. Once vitrified, polymer chain mobility becomes highly restricted, dramatically slowing the reaction rate and kinetically trapping the material in a "diffusion-controlled" glassy state [51]. If vitrification occurs prematurely—before sufficient crosslinking—this can result in high residual stress, poor adhesion, and long-term reliability concerns. With a thorough understanding of the reaction kinetics of a given material system, one can adjust the time and temperature of process steps to maintain the cure temperature

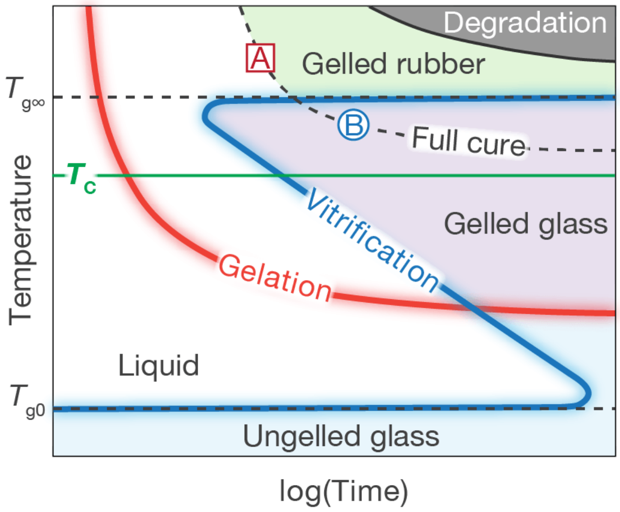

Fig. 4. Schematic of a typical Time-Temperature-Transformation (TTT) diagram illustrating the key phase transitions during thermoset curing.

above the T_g of the partially cured material to minimize those issues.

Direct visualization of the TTT diagram offers valuable guidance for process design. At a selected isothermal T_c (green line, **Fig. 4**), the material first undergoes gelation and then vitrification as curing progresses, ultimately forming a "gelled glass" state. To produce a partially cured, shape-retaining "B-stage" material, a lower T_c should be chosen such that it intersects only the vitrification curve. In contrast, achieving full cure requires selecting a T_c above $T_{g\infty}$ that avoids vitrification and intersects only the gelation curve—while remaining below the degradation threshold. In this case, the material undergoes rapid gelation and proceeds into the "gelled rubber" region.

To illustrate the impact of cure pathways on residual stress development, **Fig. 4** compares two material states, A and B, following different cure conditions: profile A (t_A, T_A) and profile B (t_B, T_B). Although both paths reach the same degree of cure—falling along the same isoconversion contour in the TTT diagram—they result in different residual stresses. Profile A achieves full cure through a shorter ($t_A < t_B$), higher-temperature ($T_A > T_B$) schedule that avoids vitrification ($T_A > T_{g\infty}$), resulting in lower residual stress. In contrast, profile B follows a longer, lower-temperature cure $T_B < T_{g\infty}$, passing through vitrification and leading to greater stress accumulation. This comparison highlights the critical role of gelation and vitrification pathways on stress development during thermoset curing. By leveraging TTT-informed chemorheological modeling, engineers can fine-tune processing conditions to minimize residual stress, maximize performance, and improve package reliability.

C. Hygrothermal Cycling During Operation

Residual stress contributes to reliability concerns in packages. Environmental and operational stressors—such as temperature fluctuations and moisture ingress (hygroscopic swelling)—can accelerate material degradation and exacerbate interface failures, ultimately reducing the device's service life.

For example, underfill materials subjected to repeated thermal cycling are prone to developing microcracks and delaminating from multiple interfaces, potentially resulting in device failure [31, 52]. Those effects are most frequently due to mismatches in the CTE among the package, die, underfill, and substrate. In such cases, thermal cycling can fatigue solder joints, leading to electrical failure. Accurate measurements of CTE, modulus, and T_g are essential for developing mechanical models that predict the cycle life of an electronic assembly. In general, it is undesirable for a material's T_g to fall within the operating temperature range of the hardware, due to the significant change in CTE that occurs near the T_g. While the decrease in modulus associated with the glass transition may partially mitigate the consequences of CTE mismatch [53, 54], comprehensive and accurate property data are essential for predictive modeling and reliability assessment. In addition to mechanical failures, moisture further complicates performance by affecting functionality—through moisture diffusivity and solubility that degrade dielectric properties and compromise signal integrity, particularly at the high switching speeds of 5G and 6G technologies. I/O signals that are sharp and high-fidelity in a dry environment can become lossy or distorted as moisture infiltrates the package. This functional degradation remains a significant concern due to constant fluctuations in moisture levels over years of use.

Understanding the evolution of residual stress and functional material properties under relevant hygrothermal conditions is important [55, 56]. Equally critical is evaluating how interfacial material properties change over time in response to these environmental stressors. Maintaining robust adhesion between polymers and adjacent materials—such as metals, oxides, or other organic layers—remains a persistent challenge in advanced packaging [57, 58]. Overcoming these challenges will require not only improved material formulations, but also advanced characterization techniques capable of assessing these behaviors under application-relevant conditions.

D. Accurate Property Measurements and Modeling

Accurate modeling of advanced packages depends on high-quality, reliable material property data. Polymers are viscoelastic, exhibiting time-, frequency-, and temperature-dependent mechanical properties [59]. Among these, the viscoelastic bulk modulus [60, 61] and Poisson's ratio [62-64] are important for predicting stress evolution [65]; however, their time and temperature dependencies are often overlooked. While simplified models that assume constant or purely elastic values may ease computation, they can lead to large discrepancies between simulation and experimental results, especially in multi-layered structures with large CTE mismatches. For example, incorporating a temperature-dependent Poisson's ratio into thermal warpage simulations improved prediction accuracy by a factor of four compared to constant-property models [66]. As packaging technologies continue to scale toward thinner geometries and finer-pitch interconnects, incorporating viscoelastic, time-dependent properties into simulations becomes not only beneficial but essential for reliable stress analysis and process design.

> *"Modeling without metrology is imagination."*
>
> —William (Bill) Chen, Advanced Semiconductor Engineering, Inc., at the 2024 Electronics Packaging Symposium

Without rigorous metrology and standardized measurement methods to facilitate interlaboratory comparisons (e.g., variations in T_g across different techniques as discussed earlier), predictive modeling remains limited. Accurate and reproducible data are critical for building reliable simulations and enabling digital twins in thermoset manufacturing. Robust metrology not only enhances modeling capabilities, but also enables fast materials screening and supports the successful deployment of new materials from research to production.

IV. ADVANCING METROLOGIES TO ADDRESS MEASUREMENT CHALLENGES

Given the complex, multi-material, and multi-scale interactions that govern the performance of polymeric

This article has been accepted for publication in IEEE Transactions on Components, Packaging and Manufacturing Technology. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TCPMT.2025.3603484

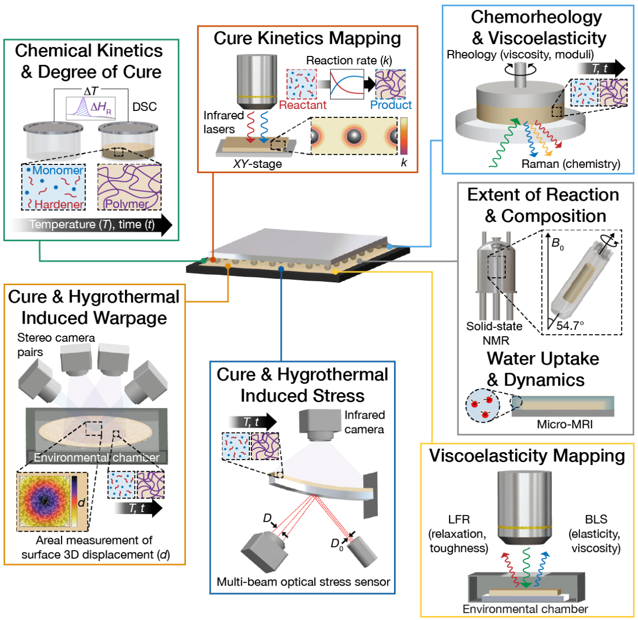

Fig. 5. Advanced metrology techniques for polymer-based packaging material characterization in the NIST CHIPS metrology project [67].

packaging materials, advanced characterization techniques are essential for gaining insights into structure–property–processing relationships and informing the development of predictive models. At the same time, ensuring measurement consistency and reproducibility across laboratories and tools is equally important. Such consistency is crucial for evaluating material properties, optimizing processes, and improving reliability assessments.

Fig. 5 presents a suite of advanced metrology techniques being developed and refined through our CHIPS Metrology Project, *Accurate Cure Kinetics, Stress, Mechanical Properties and Warpage Measurements for Next-Generation Microelectronics Packaging under Device Relevant Conditions* [67]. These tools have been integral in developing accurate cure kinetics and chemorheological models by implementing complementary approaches. These include measuring the heat of reaction directly via DSC, capturing viscoelastic transitions during polymerization with simultaneous rheo-Raman spectroscopy [37], monitoring chemical conversion by fast Fourier transform infrared spectroscopy (FTIR) [68, 69], and assessing network formation through nuclear magnetic resonance (NMR). Warpage and stress accumulation during cure are characterized using digital image correlation (DIC) [70, 71], while stress bench setups enable evaluation of stress evolution in processing and service-relevant environments [36]. Multi-mode Brillouin light scattering (BLS) and low-frequency Raman (LFR) spectroscopy [72] further support local mapping of modulus, viscoelasticity, and phonon interactions.

Ongoing collaborative efforts also explore additional in-situ techniques for tracking cure shrinkage and thermal expansion using DMA [73], TMA [74], and fiber Bragg grating (FBG) sensors [75]. Time-resolved small-angle X-ray scattering (SAXS) offers another powerful in-situ method for probing polymer network formation and phase evolution. SAXS provides unique insights into chain rearrangement by capturing heterogeneous crosslinking dynamics [76, 77]. It can also characterize processing-induced anisotropy. Ultra-small angle X-ray scattering (USAXS) can capture the size and spatial distribution of filler particles [78]. These factors are important in managing stress and interfacial adhesion. Through cutting-edge measurement science and collaborative research guided by the CHIPS Metrology Community [79], the NIST project [67] aims to help the industry bridge existing metrology gaps and build a robust foundation for the development and adoption of next-generation packaging materials.

V. OPPORTUNITIES IN MATERIALS AND PROCESSES

The rapid evolution of semiconductor packaging demands innovative materials and processes to address challenges related to warpage and stress, manufacturability, and next-generation device architectures. Here, we highlight several emerging trends discussed during the workshop.

UV-curable resins have emerged as a viable solution to mitigate thermally induced stress and warpage [80]. Their ability to enable localized, low-temperature curing enhances process control and lowers thermal budgets, though broader adoption will require the development of compatible tooling and processing methodologies.

Additively manufactured electronics (AME) are revolutionizing packaging schemes by enabling direct materials deposition with high precision and minimal waste. AME facilitates the fabrication of complex interconnects and custom device architectures but still faces challenges in material compatibility, print resolution, and process standardization [81].

The growing demand for *flexible and stretchable electronics* is driving the development of new polymeric materials with superior flexibility, low dielectric loss, and long-term mechanical stability. These materials are essential for wearable electronics, bio-integrated devices, and flexible displays, requiring careful consideration of adhesion, fatigue resistance, and environmental durability [82, 83].

Ultra-low D_k and D_f dielectrics for 5G/6G applications are emerging [84, 85]. In antenna-in-package (AiP) designs, low D_k enhances signal speed and antenna gain, while low D_f reduces dielectric loss and improves radiation efficiency. Achieving these properties requires precise molecular engineering, creating new opportunities to develop novel, low-loss dielectric polymers tailored for high-frequency electronics.

Dynamic thermosets, or vitrimers, are gaining attention for their unique ability to undergo network rearrangement without breaking down. These novel materials offer potential for stress relaxation to mitigate warpage in high-density packaging and offer recyclability benefits for sustainable packaging [86, 87].

Lastly, *next-generation TIMs* for electric vehicles and autonomous systems are being developed to deliver high thermal conductivity and long-term reliability under harsh conditions [88]. Current research is increasingly focused on integrating nanostructures to meet stringent thermal management requirements of compact, high-power electronics [89]. High-temperature aging or degradation of encapsulation materials in electronic components used in *automotive* applications is another reliability concern during long-term use [90].

VI. RESEARCH-GRADE TEST MATERIALS (RGTMS)

The path toward HI is not only diverse in the materials and metrology being explored, but also in the tailored approaches adopted across different sectors of the semiconductor ecosystem—each requiring unique solutions to address distinct challenges. A practice or solution that works well for one company, one application, or one process may not be directly transferable to another. Moreover, knowledge gained from one material or process often lacks generalizability due to the proprietary nature of commercial materials, which remain “black boxes” in terms of composition and additives. This makes quantitative comparisons between different systems difficult. In this dynamic, fast-paced landscape, RGTMs [91], a class of Reference Materials (RMs) [92], can serve as a powerful vehicle for next-generation packaging development. These well-characterized, non-proprietary model materials serve as industry benchmarks, enabling consistent measurements, supporting the development of standardized methodologies, and advancing the scientific understanding of structure–property relationships in packaging materials.

NIST is leading efforts to develop RGTMs specifically tailored for semiconductor packaging applications, with initial focus on advanced underfill materials and molding compounds. Unlike commercial materials, RGTMs offer a transparent and reproducible foundation for evaluating material properties and establishing consistent measurement protocols. These efforts aim to standardize metrologies, improve interlaboratory reproducibility, and facilitate the development of open-access materials databases for broader industry adoption.

The development of RGTMs at NIST is tightly coupled with the advancement of cutting-edge metrology techniques capable of probing structure-property relationships with spatial, temporal, and chemical resolution not previously accessible in semiconductor research. This unique “one-two punch”—combining metrology innovation with model material development—is a hallmark of NIST’s approach to advancing packaging science. This integrated strategy ensures that data generated from RGTMs is not only reproducible but also actionable, enabling the calibration and validation of predictive models for materials and process optimization.

> *“Fundamentals don’t change. Only difference is scale.”*
>
> —Jeff Gotro, Innocentrix, LLC, at the 2024 Electronics Packaging Symposium

By utilizing simple, well-defined model systems, NIST’s RGTM approach enables the systematic investigation of key variables—such as resin chemistry and filler content—providing fundamental insights applicable across different material classes and packaging architectures. While the industry continues to evolve in complexity, the underlying material science principles remain unchanged—only the scale and integration challenges have changed from yesterday to today.

The benefits of RGTMs extend beyond metrology: they accelerate materials innovation, support technology qualification, and enhance industry collaboration. By enabling a data-driven approach to material characterization, RGTMs promote open science and transparency. This, in turn, helps individual companies optimize their materials and processes and also supports the broader semiconductor ecosystem by aligning efforts between industry, academia, and government research organizations.

VII. SUMMARY AND OUTLOOK

The landscape of polymeric materials for advanced semiconductor packaging faces a host of significant challenges. First, the industry’s reliance on overseas polymer suppliers poses vulnerabilities in supply chain resilience and innovation security. Closely related to these concerns is the rapidly changing regulatory climate that can cause manufacturers to modify material formulations or withdraw products on short notice. Regulatory actions in one region can have global repercussions, affecting material availability worldwide. Second, limited information on material composition and performance data—due to proprietary constraints—complicates material selection and qualification processes. Furthermore, current characterization standards and metrology methods lack consistency and comprehensiveness, often proving inadequate for evaluating novel, complex material formulations.

To address these challenges, key takeaways from the panel discussion point to several recommendations. The semiconductor packaging community must come together to: (1) re-establish US-based supply chains for polymeric materials to reduce dependency on offshore suppliers; (2) improve transparency in material data sheets and promote standardized guidelines for material characterization; (3) develop advanced metrologies that meet stringent and evolving performance requirements of next-generation materials; and (4) foster robust, pre-competitive research collaboration among academia, government laboratories, and industry to accelerate materials development and adoption. With emerging materials requiring more than 10 years and up to 25 years to reach volume production [93], sustained collaborative efforts, such as those led by the CHIPS Metrology Community [94], are essential for driving long-term industry growth and competitiveness.

Addressing the intrinsic polymer challenges in semiconductor packaging requires a deep, fundamental understanding of polymer science. Expertise in this field is crucial for elucidating the complex relationships among material constituents, bulk and interfacial properties, processing conditions, and final material performance and reliability. As the semiconductor industry continues to push the boundaries of packaging technology, collaboration among material scientists, process engineers, and metrology experts will be essential. Advancements in measurement science will be critical to unlocking and accelerating the next generation of high-performance, reliable, and sustainable materials and processes.

Central to this effort is NIST's unique "one-two punch" strategy: the integration of metrology development with the implementation of rigorously characterized model materials. With its mission-driven mandate to pursue rigorous, foundational work, NIST is uniquely positioned to develop the advanced metrology for tomorrow's packaging materials [13]. These efforts aim to establish measurement methods that are both precise and practical. Ongoing work [36, 37, 72] is already yielding progress in characterizing the structure, chemistry, and thermomechanical behavior in highly filled, heterogeneous polymer systems—enabling insights that would be difficult to obtain through industrial R&D alone.

The strategic development and application of Research Grade Test Materials (RGTMs), are crucial for benchmarking, developing metrology methods, and elucidating fundamental structure-property-processing relationships in highly-filled polymeric materials. As the semiconductor industry continues to push the limits of 3D heterogeneous integration, the role of RGTMs will become even more critical. Ultimately, RGTMs help both individual companies and the broader semiconductor ecosystem by aligning measurement practices, simulation inputs, materials development strategies and qualification processes—paving the way for a more resilient, efficient, and collaborative framework for semiconductor innovation.

Standardizing material property reporting and enhancing data transparency, including recommendations for datasheets and measurement protocols, are critical for improving material selection and reliability prediction. Future metrology strategies must integrate multimodal measurement approaches and support open-access databases [95] to facilitate broad industry participation. Establishing a material property database that adheres to Findable, Accessible, Interoperable, Reusable (FAIR) principles, and includes Machine Learning (ML)-ready datasets, along with standardized test methods, will enable accurate modeling and simulation in semiconductor packaging technologies.

By unifying these strategies through coordinated collaboration among academia, government, and industry—and aligning with initiatives such as the Heterogeneous Integration Roadmap (HIR) [5] and the Microelectronics and Advanced Packaging Technologies (MAPT) Roadmap [96]—will help position the U.S. to maintain its technological leadership and build a more robust and resilient semiconductor ecosystem.

ACKNOWLEDGMENT

The authors sincerely thank Benson Chan and Prof. S.B. Park (Binghamton University) for the opportunity to organize the workshop at the 2024 Electronics Packaging Symposium in Binghamton, NY. We also thank project team members Drs. Sebastian Engmann, Andrew Gayle, Andrew Korovich, Alexander Landauer, Young Jong Lee, Chris Michaels, Ryan Nieuwendaal, Jianwei Tu, and Jan Obrzut (NIST) for their helpful discussions. We appreciate Dr. Fan Zhang (NIST) and Dr. Jan Ilavsky (Argonne National Laboratory) for supporting preliminary SAXS and USAXS measurements. The authors extend our gratitude to Dr. Bruce Prime (IBM, retired), Prof. Greg McKenna (North Carolina State University), Prof. Bongtae Han (University of Maryland), and Dr. Eric Schoch (Northrop Grumman Corporation) for their careful reviews and valuable feedback on various versions of the manuscript.

DISCLAIMER

These opinions, recommendations, findings, and conclusions do not necessarily reflect the views or policies of NIST or the United States Government.

REFERENCES

[1] M. G. Pecht and L. T. Nguyen, "Plastic Packaging," in *Microelectronics Packaging Handbook: Semiconductor Packaging*, R. R. Tummala, E. J. Rymaszewski, and A. G. Klopfenstein Eds. Boston, MA: Springer US, 1997, ch. 10, pp. 394-508.

[2] I. Fukuzawa, S. Ishiguro, and S. Nanbu, "Moisture Resistance Degradation of Plastic LSIs by Reflow Soldering," in *23rd International Reliability Physics Symposium*, 25-29 March 1985, pp. 192-197, doi: 10.1109/IRPS.1985.362097.

[3] D. Lu and C. P. Wong, *Materials for Advanced Packaging (Second Edition)*. Switzerland: Springer International Publishing, 2017.

[4] W. D. Weber, "Electronic Packaging," in *Encyclopedia of Polymer Science and Technology*, 2001.

[5] "Heterogeneous Integration Roadmap." [Online]. Available: http://eps.ieee.org/hir

[6] F. Sheikh, R. Nagisetty, T. Karnik, and D. Kehlet, "2.5D and 3D Heterogeneous Integration: Emerging applications," *IEEE Solid-State Circuits Magazine,* vol. 13, no. 4, pp. 77-87, 2021, doi: 10.1109/MSSC.2021.3111386.

[7] J. A. Rogers, T. Someya, and Y. Huang, "Materials and Mechanics for Stretchable Electronics," *Science,* vol. 327, no. 5973, pp. 1603-1607, 2010, doi: 10.1126/science.1182383.

[8] Y. Zhou, "Material Foundation for Future 5G Technology," *Acc. Mater. Res.,* vol. 2, no. 5, pp. 306-310, 2021, doi: 10.1021/accountsmr.0c00087.

[9] C. Tong, "5G Technology Components and Material Solutions for Hardware System Integration," in *Advanced Materials and Components for 5G and Beyond*, C. Tong Ed.: Springer Nature Switzerland, 2022, pp. 1-32.

[10] H. Kim, J. Y. Hwang, S. E. Kim, Y. C. Joo, and H. Jang, "Thermomechanical Challenges of 2.5-D Packaging: A Review of Warpage and Interconnect Reliability," *IEEE Trans. Compon., Packag., Manuf. Technol.,* vol. 13, no. 10, pp. 1624-1641, 2023, doi: 10.1109/TCPMT.2023.3317383.

[11] Y.-J. Wan, G. Li, Y.-M. Yao, X.-L. Zeng, P.-L. Zhu, and R. Sun, "Recent advances in polymer-based electronic packaging materials," *Compos. Commun.,* vol. 19, pp. 154-167, 2020, doi: 10.1016/j.coco.2020.03.011.

[12] R. Noor *et al.*, "US Microelectronics Packaging Ecosystem: Challenges and Opportunities," *arXiv:2310.11651 [eess.SY],* 2023. [Online]. Available: https://arxiv.org/abs/2310.11651.

[13] "Strategic Opportunities for U.S. Semiconductor Manufacturing: Facilitating U.S. Leadership and Competitiveness through Advancements in Measurements and Standards." [Online]. Available: https://nvlpubs.nist.gov/nistpubs/CHIPS/NIST.CHIPS.1000.pdf

[14] G. B. McKenna and S. L. Simon, "Chapter 2 - The glass transition: its measurement and underlying physics," in *Handbook of Thermal Analysis and Calorimetry*, vol. 3, S. Z. D. Cheng Ed.: Elsevier Science B.V., 2002, pp. 49-109.

[15] P. W. Anderson, "Through the Glass Lightly," *Science,* vol. 267, no. 5204, pp. 1615-1616, 1995, doi: 10.1126/science.267.5204.1615.f.

[16] G. B. McKenna and S. L. Simon, "50th Anniversary Perspective: Challenges in the Dynamics and Kinetics of Glass-Forming Polymers," *Macromolecules,* vol. 50, no. 17, pp. 6333-6361, 2017, doi: 10.1021/acs.macromol.7b01014.

[17] G. B. McKenna, "10 - Glass Formation and Glassy Behavior," in *Comprehensive Polymer Science and Supplements*, vol. 2, G. Allen and J. C. Bevington Eds. Amsterdam: Pergamon, 1989, pp. 311-362.

[18] J. D. Ferry, *Viscoelastic Properties of Polymers, 3rd Edition*. John Wiley & Sons, 1980.

[19] J. M. Hutchinson, "Physical aging of polymers," *Prog. Polym. Sci.,* vol. 20, no. 4, pp. 703-760, 1995, doi: 10.1016/0079-6700(94)00001-I.

[20] R. Seyler, *Assignment of the Glass Transition*. ASTM International, 1994.

[21] D. J. Plazek and K. L. Ngai, "The Glass Temperature," in *Physical Properties of Polymers Handbook*, J. E. Mark Ed. New York, NY: Springer New York, 2007, pp. 187-215.

[22] H. Q. Pham and M. J. Marks, "Epoxy Resins," in *Encyclopedia of Polymer Science and Technology*, 2004.

[23] T. Vidil, F. Tournilhac, S. Musso, A. Robisson, and L. Leibler, "Control of reactions and network structures of epoxy thermosets," *Prog. Polym. Sci.,* vol. 62, pp. 126-179, 2016, doi: 10.1016/j.progpolymsci.2016.06.003.

[24] Z. Zhang, P. Zhu, and C. P. Wong, "Flip-Chip Underfill: Materials, Process, and Reliability," in *Materials for Advanced Packaging*, D. Lu and C. P. Wong Eds. Cham: Springer International Publishing, 2017, pp. 331-371.

[25] J. Mewis and N. J. Wagner, "Hydrodynamic effects: Non-colloidal particles," in *Colloidal Suspension Rheology*, (Cambridge Series in Chemical Engineering. Cambridge: Cambridge University Press, 2011, pp. 36-79.

[26] "Thixotropy," in *Colloidal Suspension Rheology*, J. Mewis and N. J. Wagner Eds., (Cambridge Series in Chemical Engineering. Cambridge: Cambridge University Press, 2011, pp. 228-251.

[27] P. C. F. Møller, J. Mewis, and D. Bonn, "Yield stress and thixotropy: on the difficulty of measuring yield stresses in practice," *Soft Matter,* vol. 2, no. 4, pp. 274-283, 2006, doi: 10.1039/B517840A.

[28] P. I. Karkanas and I. K. Partridge, "Cure modeling and monitoring of epoxy/amine resin systems. II. Network formation and chemoviscosity modeling," *J. Appl. Polym. Sci.,* vol. 77, no. 10, pp. 2178-2188, 2000, doi: 10.1002/1097-4628(20000906)77:10<2178::AID-APP11>3.0.CO;2-0.

[29] T. Braun *et al.*, "How to Manipulate Warpage in Fan-out Wafer and Panel Level Packaging," in *2024 IEEE 74th Electronic Components and Technology Conference (ECTC)*, Denver, CO, USA, 2024, pp. 1-6, doi: 10.1109/ECTC51529.2024.00008.

[30] P. Praful and C. Bailey, "Warpage in wafer-level packaging: a review of causes, modelling, and mitigation strategies," *Front. Electron.,* vol. 5, 2025, doi: 10.3389/felec.2024.1515860.

[31] R. Dias and D. Goyal, "Methodology and Challenges in Characterization of 3D Package Interconnection Materials and Processes," in *Metrology and Diagnostic Techniques for Nanoelectronics (1st ed.)*, Z. Ma and D. G. Seiler Eds.: Jenny Stanford Publishing, New York, 2017.

[32] F. Hou *et al.*, "Experimental Verification and Optimization Analysis of Warpage for Panel-Level Fan-Out Package," *IEEE Trans. Compon., Packag., Manuf. Technol.,* vol. 7, no. 10, pp. 1721-1728, 2017, doi: 10.1109/TCPMT.2017.2726084.

[33] J. Lau and X. Fan, "Warpage Management in Semiconductor Packaging," in *Hybrid Bonding, Advanced Substrates, Failure Mechanisms, and Thermal Management for Chiplets and Heterogeneous Integration*, J. Lau and X. Fan Eds.: Springer Nature, Singapore, 2025, pp. 261-321.

[34] R. Tao, S. P. Phansalkar, A. M. Forster and B. Han, "Investigation of Cure Kinetics of Advanced Epoxy Molding Compound Using Dynamic Heating Scan: An Overlooked Second Reaction," in *2023 IEEE 73rd Electronic Components and Technology Conference (ECTC)*, Orlando, FL, USA, 2023, pp. 1319-1326, doi: 10.1109/ECTC51909.2023.00225.

[35] S. P. Phansalkar, Y. Jang, B. Han, R. Tao, and A. M. Forster, "Novel method to determine autocatalytic cure kinetics model constants of dual-reaction thermosets," *Mater. Sci. Eng. B,* vol. 311, p. 117829, 2025, doi: 10.1016/j.mseb.2024.117829.

[36] P. Centellas *et al.*, "Advanced Metrology Suite for Linking Residual Stress to Fundamental Properties of Thermoset Packaging Materials," in *2025 IEEE 75th Electronic Components and Technology Conference (ECTC)*, Dallas, TX, USA, 2025, pp. 432-439, doi: 10.1109/ECTC51687.2025.00078.

[37] A. P. Kotula, R. Tao, J. Tu, Y. J. Lee and G. A. Holmes, "Advanced Characterization of the Cure Kinetics of a Liquid Encapsulant," in *2025 IEEE 75th Electronic Components and Technology Conference (ECTC)*, Dallas, TX, USA, 2025, pp. 1784-1790, doi: 10.1109/ECTC51687.2025.00303.

[38] C. Strasser, E. Moukhina, and J. Hartmann, "Time–Temperature-Transformation (TTT) Cure Diagram of an Epoxy–Amine System," *Macromol. Theory Simul.,* vol. 33, no. 6, p. 2400039, 2024, doi: 10.1002/mats.202400039.

[39] P. J. Halley and M. E. Mackay, "Chemorheology of thermosets—an overview," *Polym. Eng. Sci.,* vol. 36, no. 5, pp. 593-609, 1996, doi: 10.1002/pen.10447.

[40] P. J. Halley, "A new chemorheological analysis of highly filled thermosets used in integrated circuit packaging," *J. Appl. Polym. Sci.,* vol. 64, no. 1, pp. 95-106, 1997, doi: 10.1002/(SICI)1097-4628(19970404)64:1<95::AID-APP8>3.0.CO;2-M.

[41] G. Wisanrakkit and J. K. Gillham, "The glass transition temperature (Tg) as an index of chemical conversion for a high-Tg amine/epoxy system: Chemical and diffusion-controlled reaction kinetics," *J. Appl. Polym. Sci.,* vol. 41, no. 11-12, pp. 2885-2929, 1990, doi: 10.1002/app.1990.070411129.

[42] G. Wisanrakkit and J. K. Gillham, "Continuous heating transformation (CHT) cure diagram of an aromatic amine/epoxy system at constant heating rates," *J. Appl. Polym. Sci.,* vol. 42, no. 9, pp. 2453-2463, 1991, doi: 10.1002/app.1991.070420911.

[43] R. B. Prime, "Thermosets," in *Thermal Characterization of Polymeric Materials (Second Edition)*, vol. 2, E. A. Turi Ed. San Diego, California: Academic Press, 1997, ch. 6, pp. 1379-1776.

[44] J. D. Russell, M. S. Madhukar, M. S. Genidy, and A. Y. Lee, "A New Method to Reduce Cure-Induced Stresses in Thermoset Polymer Composites, Part III: Correlating Stress History to Viscosity, Degree of Cure, and Cure Shrinkage," *J. Compos. Mater.,* vol. 34, no. 22, pp. 1926-1947, 2000, doi: 10.1106/uy9u-f2qw-2fkk-91kg.

[45] P. Prasatya, G. B. McKenna, and S. L. Simon, "A Viscoelastic Model for Predicting Isotropic Residual Stresses in Thermosetting Materials: Effects of Processing Parameters," *J. Compos. Mater.,* vol. 35, no. 10, pp. 826-848, 2001, doi: 10.1177/a037322.

[46] J. B. Enns and J. K. Gillham, "Time–temperature–transformation (TTT) cure diagram: Modeling the cure behavior of thermosets," *J. Appl. Polym. Sci.,* vol. 28, no. 8, pp. 2567-2591, 1983, doi: 10.1002/app.1983.070280810.

[47] S. L. Simon and J. K. Gillham, "Thermosetting cure diagrams: Calculation and application," *J. Appl. Polym. Sci.,* vol. 53, no. 6, pp. 709-727, 1994, doi: 10.1002/app.1994.070530601.

[48] P. J. Flory, *Principles of Polymer Chemistry*. Ithaca, NY: Cornell University Press, 1953.

[49] H. H. Winter and F. Chambon, "Analysis of Linear Viscoelasticity of a Crosslinking Polymer at the Gel Point," *J. Rheol.,* vol. 30, no. 2, pp. 367-382, 1986, doi: 10.1122/1.549853.

[50] H. H. Winter, "Gel Point," in *Encyclopedia of Polymer Science and Technology*, 2016, pp. 1-15.

[51] S. L. Simon and J. K. Gillham, "Reaction kinetics and TTT cure diagrams for off-stoichiometric ratios of a high-Tg epoxy/amine system," *J. Appl. Polym. Sci.,* vol. 46, no. 7, pp. 1245-1270, 1992, doi: 10.1002/app.1992.070460714.

[52] W.-S. Lei and A. Kumar, "Delamination and Reliability Issues in Packaged Devices," in *Adhesion in Microelectronics*, K. L. Mittal and T. Ahsan Eds.: Scrivener Publishing, 2014, pp. 267-312.

[53] R. Tao and S. L. Simon, "Pressure-volume-temperature and glass transition behavior of silica/polystyrene nanocomposite," *J. Polym. Sci. B Polym. Phys.,* vol. 53, no. 16, pp. 1131-1138, 2015, doi: 10.1002/polb.23749.

[54] Q. Li, S. A. Hutcheson, G. B. McKenna, and S. L. Simon, "Viscoelastic properties and residual stresses in polyhedral oligomeric silsesquioxane-reinforced epoxy matrices," *J. Polym. Sci. B Polym. Phys.,* vol. 46, no. 24, pp. 2719-2732, 2008, doi: 10.1002/polb.21609.

[55] E. H. Wong, R. Rajoo , S. W. Koh , and T. B. Lim, "The Mechanics and Impact of Hygroscopic Swelling of Polymeric Materials in Electronic Packaging," *J. Electron. Packag.,* vol. 124, no. 2, pp. 122-126, 2002, doi: 10.1115/1.1461367.

[56] H. Ardebili, W. Ee Hua, and M. Pecht, "Hygroscopic swelling and sorption characteristics of epoxy molding compounds used in electronic packaging," *IEEE Transactions on Components and Packaging Technologies,* vol. 26, no. 1, pp. 206-214, 2003, doi: 10.1109/TCAPT.2002.806172.

[57] V. K. Khanna, "Adhesion–delamination phenomena at the surfaces and interfaces in microelectronics and MEMS structures and packaged devices," *J. Phys. D: Appl. Phys.,* vol. 44, no. 3, p. 034004, 2011, doi: 10.1088/0022-3727/44/3/034004.

[58] P. Viswanadham, "Role of Adhesion Phenomenon in the Reliability of Electronic Packaging," in *Adhesion in Microelectronics*, K. L. Mittal and T. Ahsan Eds.: Scrivener Publishing, 2014, pp. 211-265.

[59] S. L. Simon, G. B. Mckenna, and O. Sindt, "Modeling the evolution of the dynamic mechanical properties of a commercial epoxy during cure after gelation," *J. Appl. Polym. Sci.,* vol. 76, no. 4, pp. 495-508, 2000, doi: 10.1002/(SICI)1097-4628(20000425)76:4<495::AID-APP7>3.0.CO;2-B.

[60] R. Tao and S. L. Simon, "Bulk and Shear Rheology of Silica/Polystyrene Nanocomposite: Reinforcement and Dynamics," *J. Polym. Sci. B Polym. Phys.,* vol. 53, no. 9, pp. 621-632, 2015, doi: 10.1002/polb.23669.

[61] S. P. Phansalkar, R. Mittakolu and B. Han, "Time-dependent Bulk Behavior of Cured Epoxy Molding Compound," in *2023 IEEE 73rd Electronic Components and Technology Conference (ECTC)*, Orlando, FL, USA, 2023, pp. 2093-2100, doi: 10.1109/ECTC51909.2023.00358.

[62] D. J. O'Brien, N. R. Sottos, and S. R. White, "Cure-dependent Viscoelastic Poisson's Ratio of Epoxy," *Exp. Mech.,* vol. 47, no. 2, pp. 237-249, 2007, doi: 10.1007/s11340-006-9013-9.

[63] H. Lu, X. Zhang, and W. G. Knauss, "Uniaxial, shear, and poisson relaxation and their conversion to bulk relaxation: Studies on poly(methyl methacrylate)," *Polym. Compos.,* vol. 18, no. 2, pp. 211-222, 1997, doi: 10.1002/pc.10275.

[64] N. W. Tschoegl, W. G. Knauss, and I. Emri, "Poisson's Ratio in Linear Viscoelasticity – A Critical Review," *Mech. Time-Depend. Mat.,* vol. 6, no. 1, pp. 3-51, 2002, doi: 10.1023/A:1014411503170.

[65] S. P. Phansalkar, C. Kim, and B. Han, "Effect of critical properties of epoxy molding compound on warpage prediction: A critical review," *Microelectron. Reliab.,* vol. 130, p. 114480, 2022, doi: 10.1016/j.microrel.2022.114480.

[66] J. Kim *et al.*, "Enhancing predictability of thermal warpage by applying temperature-dependent Poisson's ratio of epoxy molding compound," *Polym. Test.,* vol. 125, p. 108140, 2023, doi: 10.1016/j.polymertesting.2023.108140.

[67] "NIST CHIPS Metrology R&D Project: Accurate Cure Kinetics, Stress, Mechanical Properties and Warpage." [Online]. Available: https://www.nist.gov/programs-projects/accurate-cure-kinetics-stress-mechanical-properties-and-warpage

[68] G. Nikolic, S. Zlatkovic, M. Cakic, S. Cakic, C. Lacnjevac, and Z. Rajic, "Fast Fourier Transform IR Characterization of Epoxy GY Systems Crosslinked with Aliphatic and Cycloaliphatic EH Polyamine Adducts," *Sensors,* vol. 10, no. 1, pp. 684-696, 2010, doi:10.3390/s100100684.

[69] M. G. González, J. C. Cabanelas, and J. Baselga, "Applications of FTIR on Epoxy Resins - Identification, Monitoring the Curing Process, Phase Separation and Water Uptake," in *Infrared Spectroscopy - Materials Science, Engineering and Technology*, T. Theophanides Ed.: IntechOpen, 2012, pp. 261–284.

[70] Y. Niu, S. Shao, S. B. Park, and C. L. Kao, "A Novel Speckle-Free Digital Image Correlation Method for In Situ Warpage Characterization," *IEEE Trans. Compon., Packag., Manuf. Technol.,* vol. 7, no. 2, pp. 276-284, 2017, doi: 10.1109/TCPMT.2016.2635581.

[71] G. Sun and S. Zhang, "A review on warpage measurement metrologies for advanced electronic packaging," *Microelectron. Reliab.,* vol. 160, p. 115456, 2024, doi: 10.1016/j.microrel.2024.115456.

[72] S. Engmann, A. J. Gayle, S. K. Romberg, C. L. Soles and C. A. Michaels, "A Dual Mode Brillouin/Low-Frequency Raman Spectroscopy Microscope for Local Mechanical Property Imaging for Semiconductor Packaging Materials," in *2025 IEEE 75th Electronic Components and Technology Conference (ECTC)*, Dallas, TX, USA, 2025, pp. 1694-1701, doi: 10.1109/ECTC51687.2025.00288.

[73] K. F. Schoch, P. A. Panackal, and P. P. Frank, "Real-time measurement of resin shrinkage during cure," *Thermochim. Acta,* vol. 417, no. 1, pp. 115-118, 2004, doi: 10.1016/j.tca.2003.12.027.

[74] H. Yu, S. G. Mhaisalkar, and E. H. Wong, "Cure shrinkage measurement of nonconductive adhesives by means of a thermomechanical analyzer," *J. Electron. Mater.,* vol. 34, no. 8, pp. 1177-1182, 2005, doi: 10.1007/s11664-005-0248-5.

[75] C. Kim, S. P. Phansalkar, H.-S. Lee, and B. Han, "Measurement of effective cure shrinkage of epoxy-based molding compound by fiber Bragg grating sensor using two-stage curing process," *J. Appl. Polym. Sci.,* vol. 139, no. 6, p. 51620, 2022, doi: 10.1002/app.51620.

[76] M. Aoki, A. Shundo, R. Kuwahara, S. Yamamoto, and K. Tanaka, "Mesoscopic Heterogeneity in the Curing Process of an Epoxy–Amine System," *Macromolecules,* vol. 52, no. 5, pp. 2075-2082, 2019, doi: 10.1021/acs.macromol.8b02416.

[77] T. Hoshino, Y. Okamoto, A. Yamamoto, and H. Masunaga, "Heterogeneous dynamics in the curing process of epoxy resins," *Sci. Rep.,* vol. 11, no. 1, p. 9767, 2021, doi: 10.1038/s41598-021-89155-x.

[78] F. Zhang and J. Ilavsky, "Bridging length scales in hard materials with ultra-small angle X-ray scattering - a critical review," *IUCrJ,* vol. 11, no. 5, pp. 675-694, 2024, doi: 10.1107/S2052252524006298.

[79] "CHIPS Metrology Community Charter Outline." [Online]. Available: https://www.nist.gov/system/files/documents/2024/08/27/CHIPS%20Metrology%20Charter%20Outline-508C.pdf

[80] M. Schindler *et al.*, "Development of UV-curable molding materials with minimum die-shift for FOWLP/FOPLP," in *2024 IEEE 74th Electronic Components and Technology Conference (ECTC)*, Denver, CO, USA, 2024, pp. 860-864, doi: 10.1109/ECTC51529.2024.00138.

[81] "Chapter 25: Additive Manufacturing & Additive Electronics for Heterogeneous Integration," *in Heterogeneous Integration Roadmap, 2024 Edition*. [Online]. Available: https://eps.ieee.org/images/files/HIR_2024/HIR_2024_ch25_AME.pdf

[82] D. Baran, D. Corzo, and G. T. Blazquez, "Flexible Electronics: Status, Challenges and Opportunities," *Front. Electron.,* Specialty Grand Challenge vol. 1, 2020, doi: 10.3389/felec.2020.594003.

[83] L. Li, L. Han, H. Hu, and R. Zhang, "A review on polymers and their composites for flexible electronics," *Mater. Adv.,* vol. 4, no. 3, pp. 726-746, 2023, doi: 10.1039/D2MA00940D.

[84] K. Hamada *et al*., "Novel High Reliability and Low Dk/Df Dielectric RDL Material for High Frequency 5G Applications," in *2023 IEEE 73rd Electronic Components and Technology Conference (ECTC)*, Orlando, FL, USA, 2023, pp. 54-59, doi: 10.1109/ECTC51909.2023.00018.

[85] T. Kakutani *et al*., "Material Design and High Frequency Characterization of Novel Ultra-Low Loss Dielectric Material for 5G and 6G Applications," in *2021 IEEE 71st Electronic Components and Technology Conference (ECTC)*, San Diego, CA, USA, 2021, pp. 538-543, doi: 10.1109/ECTC32696.2021.00096.

[86] H. Zhang *et al.*, "Aromatic disulfide epoxy vitrimer packaged electronic devices: Nondestructive healing and recycling," *Polymer,* vol. 255, p. 125163, 2022, doi: 10.1016/j.polymer.2022.125163.

[87] M. A. Rashid, M. A. Islam, M. N. Hasan, M. N. N. Anu, and M. H. Ikbal, "A critical review of dynamic bonds containing curing agents for epoxy resin: Synthesis, challenges, and emerging applications," *Polym. Degrad. Stab.,* vol. 229, p. 110980, 2024, doi: 10.1016/j.polymdegradstab.2024.110980.

[88] K. C. Otiaba, N. N. Ekere, R. S. Bhatti, S. Mallik, M. O. Alam, and E. H. Amalu, "Thermal interface materials for automotive electronic control unit: Trends, technology and R&D challenges," *Microelectron. Reliab.,* vol. 51, no. 12, pp. 2031-2043, 2011, doi: 10.1016/j.microrel.2011.05.001.

[89] Y. Zhang, J. Ma, N. Wei, J. Yang, and Q.-X. Pei, "Recent progress in the development of thermal interface materials: a review," *Phys. Chem. Chem. Phys.,* vol. 23, no. 2, pp. 753-776, 2021, doi: 10.1039/D0CP05514J.

[90] A. Inamdar, Y.-H. Yang, A. Prisacaru, P. Gromala, and B. Han, "High temperature aging of epoxy-based molding compound and its effect on mechanical behavior of molded electronic package," *Polym. Degrad. Stab.,* vol. 188, p. 109572, 2021, doi: 10.1016/j.polymdegradstab.2021.109572.

[91] C. Beauchamp *et al.*, "Metrological Tools for the Reference Materials and Reference Instruments of the NIST Material Measurement Laboratory," (in en), *Special Publication (NIST SP), National Institute of Standards and Technology, Gaithersburg, MD,* 2020, doi: 10.6028/NIST.SP.260-136-2020.

[92] "NIST Reference Materials." [Online]. Available: https://www.nist.gov/reference-materials

[93] "Chapter 15: Materials and Emerging Research Materials " *in Heterogeneous Integration Roadmap, 2019 Edition*. [Online]. Available: https://eps.ieee.org/images/files/HIR_2019/HIR1_ch15_materials.pdf

[94] "CHIPS Metrology Community." [Online]. Available: https://www.nist.gov/chips/metrology-community

[95] "The Metrology Exchange to Innovate in Semiconductors (METIS) data exchange ecosystem," https://www.nist.gov/programs-projects/metis.

[96] "Microelectronics and Advanced Packaging Technologies Roadmap." [Online]. Available: https://srcmapt.org/