Domestic Build-Up Film Advancing Fan-Out Wafer-Level Packaging (FOWLP) Through the SHIELD USA Program

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Abstract

Build-up films (BUF) serve as critical dielectric layers in advanced package substrates, where they enable fine pitch interconnects, multilayer redistribution routing, and the high-density integration required for next generation semiconductor devices. These engineered polymeric dielectrics are formulated to achieve a combination of low dielectric constant (Dk) and low dissipation factor (Df), while maintaining excellent thermal, mechanical, and electrical reliability. Key material characteristics such as rheological behavior during lamination, glass transition temperature (Tg), coefficient of thermal expansion (CTE), modulus, and copper adhesion strength must be precisely balanced to ensure robust multilayer stack performance. These properties play essential roles in managing warpage, interfacial integrity, stress distribution, and long-term reliability, particularly as package architectures push toward sub 2 µm line and-space requirements. The properties of Rogers BUF material that is incorporated into the processing of the Fan-Out Wafer-Level Packaging (FOWLP) process led by ASU and Deca through the SHIELD USA (Substrate Heterogeneous Integration Enabling Leadership Demonstration for the USA) program funded under the CHIPS and Science Act will be presented.

Key words

Build-up Film, FOWLP, Heterogenous Integration, Low loss Dielectric Material, MDx, SHIELD USA

I. Introduction

The continued scaling of semiconductor packaging toward higher input/output (I/O) density, finer interconnect pitch, and increased functional integration has placed significant demands on dielectric materials used in advanced package substrates [1]. Build-up films (BUF) serve as critical insulating layers that enable multilayer redistribution routing and fine-line patterning, supporting the high-density interconnect architectures required for next-generation devices [2]. These materials are particularly important in emerging platforms such as Fan-Out Wafer-Level Packaging (FOWLP) and 2.5D/3D integration, where both electrical performance and mechanical reliability are highly sensitive to material properties [2], [3].

To meet these requirements, BUF must be engineered to achieve a balance of electrical, thermal, and mechanical characteristics. Low dielectric constant (Dk) and dissipation factor (Df) are essential for minimizing signal propagation delay and high-frequency losses [4]. At the same time, thermal-mechanical properties such as glass transition temperature (Tg), coefficient of thermal expansion (CTE), and elastic modulus must be optimized to control stress, mitigate warpage, and ensure dimensional stability [2], [5], [6]. Strong adhesion to copper interfaces is also required to maintain interfacial integrity under thermal cycling and mechanical loading conditions [7].

In addition to intrinsic material properties, processability plays a critical role in successful integration. During lamination, the rheological behavior of the film must enable sufficient flow to achieve conformal coverage over underlying topography while preventing void formation [3]. Controlled curing profiles are necessary to ensure complete polymer crosslinking, which directly impacts the final mechanical strength, thermal stability and moisture absorption of the dielectric layer [6].

Within this context, the SHIELD USA (**S**ubstrate **H**eterogeneous **I**ntegration **E**nabling **L**eadership **D**emonstration for the USA) program, led by Arizona State University (ASU) in collaboration with Deca Technologies (Deca) aims to advance domestic capabilities in advanced semiconductor packaging and heterogeneous integration. As part of this effort, Rogers Corporation has developed a domestically manufactured BUF specifically designed for integration into Deca's M Series™ Direct (MDx) FOWLP process. In this architecture, the Rogers BUF functions as

the primary insulating dielectric layer, enabling ultra-high-density redistribution layers while maintaining the electrical performance required for high-frequency operation.
The collaboration between Rogers, ASU, and Deca represents a critical step toward establishing a robust domestic supply chain for advanced packaging materials and processes. By incorporating Rogers BUF into the SHIELD USA platform, this work demonstrates the feasibility of integrating a domestically developed dielectric material into a leading-edge FOWLP manufacturing flow, supporting both technological advancement and supply chain resilience.
In this study, the electrical, thermal, and mechanical properties of the Rogers BUF are presented, along with its dielectric performance up to millimeter-wave frequencies and its stability under accelerated environmental stress conditions. Additionally, the material's process compatibility with FOWLP fabrication including lamination, planarization, and via formation within the Deca MDx process is evaluated.

II. Experimental Methods

A. BUF Lamination

Lamination was achieved using either a vacuum hydraulic lamination process or via vacuum lamination. For a vacuum hydraulic process, the cycle consisted of a temperature ramp to 125°C followed by a 15-minute hold at 145 psi, then ramped to 180°C with a 60-minute hold and subsequently cooled under constant pressure.

B. Spit Post Dielectric Resonator (SPDR) method

The Dk and Df were measured using the SPDR method following IPC-TM-650 Method 2.5.5.15. In this test, a flat, metal-free dielectric sample (approximately 20 mil thick) is placed between two dielectric resonators inside a shielded cavity and measured at a frequency of approximately 10 GHz. The presence of the sample causes a shift in the resonant frequency and a change in the quality factor (Q) of the resonator. The frequency shift is used to calculate Dk, while the change in Q is used to determine Df. Because the electric field is oriented perpendicular to the sample surface, this method provides accurate in plane (XY plan) dielectric characterization of thin, low-loss laminate materials.

C. Microstrip Differential Phase Method

The microstrip differential phase length (MDPL) method is a wideband transmission-line technique used to extract the dielectric constant (Dk) of a substrate by analyzing phase response. The method employs two microstrip lines of identical geometry but different lengths (typically in a 3:1 or 4:1 ratio), and the phase difference ($\Delta\Phi$) between their S21 responses is measured using a vector network analyzer. This phase difference, together with the known length difference (ΔL), is used to determine the effective dielectric constant (ε_{eff}) as a function of frequency. The measured ε_{eff} is then compared with values generated from closed-form transmission line models, and the material Dk is iteratively adjusted until agreement is achieved, enabling extraction of Dk versus frequency over a broad range.

D. Thermal Techniques (TGA, DMA)

Thermogravimetric analysis (TGA) was performed in accordance with ASTM D3850-19 to determine the thermal degradation temperature corresponding to 5% weight loss (Td_5%) of the organic components. Dynamic mechanical analysis (DMA) was conducted following IPC-TM-650 Method 2.4.24 to evaluate the storage modulus and glass transition temperature (Tg) of the dominant phase.

E. TMA

The CTE was measured using thermomechanical analysis (TMA) in accordance with IPC-TM-650 Method 2.4.41. In this method, a small dielectric specimen is subjected to a controlled temperature ramp while dimensional changes are continuously monitored under a constant load. The change in thickness as a function of temperature is used to calculate the CTE. The build-up film was laminated into a 60-mil laminate and evaluated in the X- and Y-directions over a temperature range of -50 °C to 250 °C to assess thermal expansion behavior relevant to material processing and reliability. The dimensional change with temperature was further analyzed over sub ranges of -50 °C –150 °C and 150–250 °C interval.

F. Highly Accelerated Stress Test (HAST)

The dielectric properties of the cured material were evaluated under unbiased HAST conditions. Two environmental conditions were investigated: (1) 130°C/85% relative humidity for a duration of 96 hrs and (2) 150°C/95% relative humidity, for a duration of 168 hours. (Dk and Df were measured before and after conditioning using the SPDR method at 10 GHz.

III. Results and Discussion

A. Rogers BUF Material Property

Rogers BUF is engineered to provide a well-balanced combination of electrical, thermal, and mechanical properties required for advanced packaging applications. Table 1 shows that at 10 GHz, the material exhibits a dielectric constant (Dk) of approximately 3.0–3.1 and a low dissipation factor (Df) on the order of 0.0011, enabling low-loss signal transmission suitable for high-frequency and

millimeter-wave applications. The material demonstrates a glass transition temperature (Tg) of approximately 187 °C (TMA) to 229 °C (DMA), indicating strong thermal stability during processing and operation. The coefficient of thermal expansion (CTE) in the XY direction is controlled at approximately 25 µm/m°C below Tg, supporting dimensional stability and minimizing mismatch with adjacent materials.

Mechanically, the cured BUF exhibits a modulus of approximately 6 GPa at 25 °C that decreases with temperature, enabling sufficient stiffness for structural support while maintaining some compliance during thermal cycling. The material also demonstrates good adhesion to copper, with peel strengths approaching approximately 2 pounds per linear inch (PLI) depending on the interface, ensuring robust interfacial integrity in multilayer structures. In addition, the BUF maintains low moisture absorption of approximately 0.06–0.12%, which is critical for preserving dielectric performance and reliability under humid environments. Thermal stability is further supported by a decomposition temperature exceeding 400 C (Td approximately 437 °C), confirming the material's suitability for high-temperature processing conditions.

These properties enable the Rogers BUF to function effectively as an insulating dielectric layer in advanced FOWLP architecture, where it supports fine-line patterning, maintains electrical performance at high frequencies, and withstands the thermal and mechanical stresses associated with fabrication and processing environments.

Table I: Material properties for Rogers BUF. Average properties of four pilot trials.

Material Properties	**Conditions**	**Units**	**Property Avg**	**Range +/-**
Dk	@10 GHz		3.01	0.005
Df	@10 GHz		0.00114	0.00005
CTE XY- Axis	-50°C to 150°C	µm/ m°C	25	2
	150°C to 250°C	µm/ m°C	74	8
Tg	by TMA	°C	187	2
	by DMA	°C	229	1
Minim Melt Viscosity	by ARES-G2	Poise	73871	4400
Modulus	by DMA at 25°C	MPa	6027	73
	by DMA at 150°C	MPa	3262	57
Peel Strength (Smooth Cu Foil)	BUF Side 1	PLI	1.96	0.14
	BUF Side 2	PLI	0.98	0.13
(Td_5 %)	by TGA	°C	437	3
H_2O Absorption	24 hrs at RT	%	0.06	0.00

B. Electrical Testing using microstrip differential phase length (MDPL) method

The high-frequency electrical performance measured using the MDPL method correlates well with the bulk dielectric properties summarized in Table I. The microstrip differential phase method utilizes a 5 mil thick Rogers BUF laminate prepared with smooth copper foil. The low Dk and Df of Rogers BUF help signals travel with minimal distortion and loss. As a result, the material provides a stable phase response (consistent signal timing) and low insertion loss (minimal signal weakening) over a wide range of frequencies. This performance is maintained even at millimeter-wave frequencies, as shown by the measured Dk in Fig. 1 and insertion loss data in Fig. 2. The consistent phase response is important at high frequencies where even a small timing change can cause signal mismatch and degraded performance. The material's low moisture uptake and high thermal stability help preserve the dielectric properties under varying environmental and processing conditions, preventing dispersion or degradation at high frequencies. The stability of the Dk with increasing frequencies is also consistent with the materials low polarizability and controlled molecular design while the low loss tangent aligns with limited dipolar and conductive loss mechanisms.

Overall, these results demonstrate that the material maintains stable electromagnetic performance over a wide bandwidth, making it suitable for high-frequency applications.

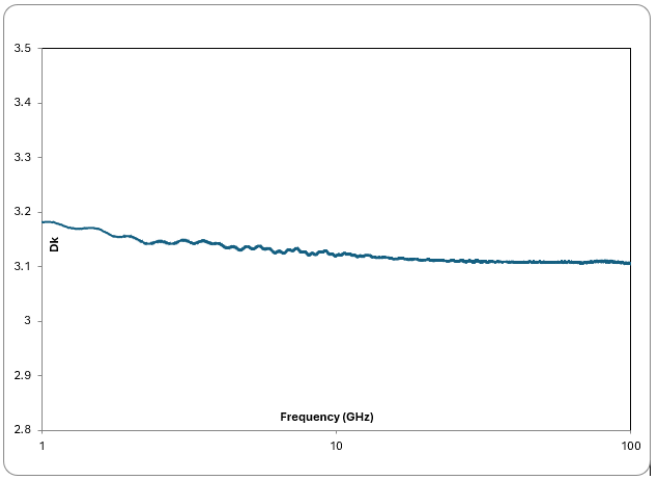


Fig. 1: Microstrip differential phase length method, Design Dk vs. Frequency, using 5mil Rogers BUF with smooth profile copper showing that Dk remains low and nearly constant as frequency increases.

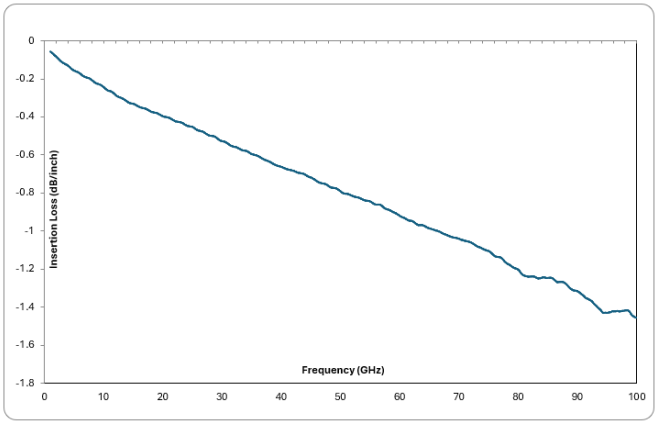


Fig. 2: Microstrip differential phase length method, Insertion loss vs. Frequency, using circuits built on 5mil Rogers BUF with smooth profile copper showing that signal loss remains low even at high frequencies.

C. Dielectric Stability Under Unbiased HAST Conditions

Table II and III show the unbiased HAST data evaluating the dielectric stability of Rogers BUF material under extreme temperature and humidity conditions, simulating long-term reliability in accelerated timeframes. The test conditions 1 at 130°C/85% RH (Table II) and condition 2 at 150°C/95% RH (Table III) are designed to stress the material and assess its susceptibility to moisture-induced degradation.

Under both stress conditions, the Dk showed only a minor increase, from approximately 3.08–3.09 to approximately 3.12. This corresponds to approximately 1.1–1.2% change, which remains well below the material design limit of Dk < 3.2, indicating that moisture uptake has minimal impact on the material's permittivity

Table II. Dk and Df after uHAST condition 1: 130 C 85% relative humidity (96hrs).

Dielectric properties	**Initial**	**After Conditioning**
Dk @ 10 GHz	3.08	3.12
Df @ 10 GHz	0.0012	0.0018

Table III. Dk and Df after uHAST condition 2: 150 C 95 % relative humidity (168 hrs).

Dielectric properties	**Initial**	**After Conditioning**
Dk @ 10 GHz	3.09	3.12
Df @ 10 GHz	0.0012	0.0020

In contrast, the Df exhibited a more pronounced relative increase, rising to 0.0018 and 0.0020 for conditions 1 and 2, respectively. This increase is attributed to moisture uptake, which introduces additional dielectric loss through dipolar relaxation and increased conduction pathways. Despite this increase, the absolute Df values remain low and within the acceptable range for high-frequency, low-loss applications, demonstrating that the material retains its functional electrical performance even after severe environmental exposure

Overall, the HAST data indicate that the BUF material possesses strong resistance to moisture-induced degradation. The small shift in dielectric constant and the controlled increase in dissipation factor, combined with the inherently low moisture absorption of the material, demonstrates that the BUF maintains reliable electrical performance even after prolonged exposure to high temperature and humidity environments and that the material still maintains low-loss performance suitable for high-frequency applications.

D. Shelf-life studies

Shelf-life studies were conducted to evaluate the stability of the uncured Rogers BUF under different storage conditions and to determine the impact on dielectric performance over time. The material was stored under three environments: room temperature, refrigerated conditions, and elevated temperature (40 °C), and monitored over a period of up to seven months. After 7 months, the dielectric performance is largely unaffected by the various storage conditions. The measured Dk & Df remained relatively consistent at 10 GHz at approximately 3.10 and approximately 0.00135 across all three storage conditions, showing no discernible difference between them. This stability suggests that the material does not undergo significant premature curing, phase separation or chemical degradation during storage.

E. BUF film processing for FOWLP

The BUF is designed to be compatible with FOWLP processing and is currently being evaluated as the first domestically fabricated BUF to be used as the insulative dielectric for the substrate layer in Deca's M-Series™ Direct (MDx) process, as illustrated in Figure 3. In this process, BUF is applied and cured using a hydraulic press (Step 6), although vacuum lamination is also a potential option and is still under evaluation. This is followed by grinding (Step 7), where the BUF layer is thinned by the grinding process to expose the underlying copper features. Rogers BUF was successfully applied and processed through grinding using the Deca MDx process in collaboration with Deca and ASU, as shown in Figure 3. The results demonstrate ultra-high density planarized wiring layers based on Deca's MDx™ process encapsulated by the developed Rogers' BUF resulting in 2 µm L&S (Figure 3a). Along with the redistribution wiring, scaled 5

µm diameter vias have been demonstrated (Fig. 3b). Unlike traditional photopolymer vias, MDx vias are defined by additively electroplated Cu vias in photoresist over each wiring layer. The vias are then encapsulated with the Rogers' BUF dielectric and planarized to reveal the top of the vias (Fig. 3c). Any shape via is allowed in each layer, which Rogers BUF was able to flow and fill. In contrast, mechanically or laser drilled vias offer only circular shapes with typically one via diameter allowed per layer. A simplified process flow of Dea's MDx process is shown in Fig 4.

Rogers BUF is favorable for FOWLP because it combines low loss electrical performance, stable dielectric behavior, fine-line process compatibility, and robust reliability under thermal and moisture stress. These attributes enable higher signal integrity, tighter scaling, and improved reliability, making it suited for advanced high-frequency fan-out packaging

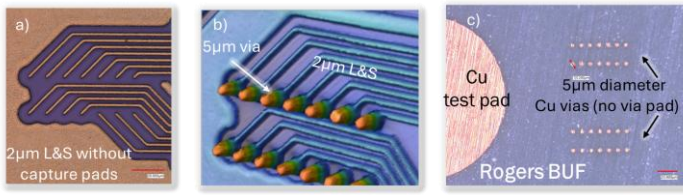


Fig. 3: (a) Ultra-high density planarized wiring layers at 2µm L&S (b) 5µm diameter vias plated on 2µm traces without capture pads (c) MDx RDL is encapsulated by the Rogers BUF, then planarized and the 5µm vias are revealed [8]

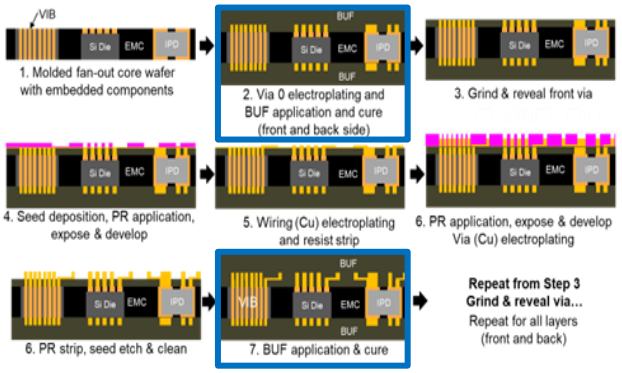


Fig. 4: Simplified process flow for Deca M-Series™ Direct (MDx) ultra-high density planarized layers [8] highlighting the addition of the BUF layer.

F. Additional Processing of the BUF

In addition to compatibility with the Deca's MDx process, the Rogers BUF is being evaluated for integration into alternative fabrication flows, including vacuum lamination and semi-additive processing (SAP). Preliminary work has demonstrated that the BUF can be successfully laminated onto substrates with copper features using vacuum lamination, followed by post-cure to achieve full crosslinking. Cross-sectional SEM analysis shows that the BUF fully encapsulates both fine-line features (2 µm line/space), Fig. 5a, and via structures (5 µm diameter), Fig. 5b, without void formation. This confirms that the material possesses appropriate rheological behavior during processing, enabling uniform coverage and planarization across complex geometries. The observed defect-free interfaces and complete fill are critical for maintaining electrical integrity and reliability in high-density packaging applications.

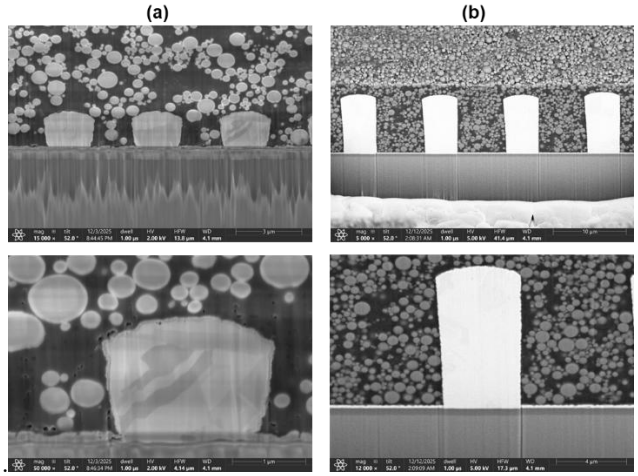


Fig. 5: SEM cross-section image of Rogers BUF film showing complete flow and fill over (a) 2 µm L/S copper features and (b) 5 µm via.

Laser drilling was evaluated to assess the compatibility of the BUF material for via formation in advanced packaging applications. UV laser was used to create smaller vias in the range 25- 40 µm, while CO_2 laser drilling was applied for larger vias of 50 µm. Cross-section analysis using SEM confirmed clean via formation with well-defined sidewalls, indicating that the BUF responds well to both laser wavelengths (Figure 6). These results demonstrate that Rogers BUF is compatible with standard laser drilling processes and supports the formation of fine vias required for high-density interconnect structures.

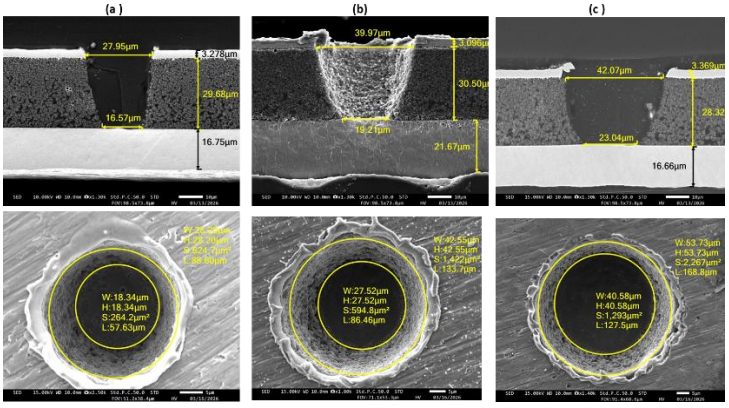


Fig. 6: SEM cross-section images of Rogers BUF film showing laser-drilled vias of a 30 µm BUF of varying diameters (left to right (a) 25 µm, (b) 40 µm and (c)50 µm.

While the MDx process enables ultra-high-density patterning through an additive approach, semi-additive processing (SAP) remains a critical complementary technology in advanced substrate manufacturing. SAP is widely used to fabricate fine line and space redistribution layers, where thin seed layers are patterned and selectively plated to build copper features with high resolution and controlled geometry. Ensuring compatibility with SAP expands Rogers BUF material's applicability beyond MDx, enabling integration into mainstream substrate manufacturing and heterogeneous integration platforms. Additional work is currently underway to further evaluate the material's performance and expand processing compatibility.

IV. Conclusion

Rogers BUF demonstrates a balanced combination of low-loss dielectric performance, with a Dk of approximately 3.0–3.1 and a Df of ~0.0011 at 10 GHz, together with stable thermomechanical reliability. The material exhibits a CTE of 25 ppm/°C across the -50°C to 150°C temperature range, making it highly suitable for advanced packaging applications.

High-frequency characterization and HAST testing confirm stable dielectric performance and strong resistance to moisture-induced degradation, with Dk and Df remaining below 3.2 and 0.002, respectively, at 10 GHz. Rogers BUF also demonstrates excellent shelf-life stability under multiple storage conditions, including room-temperature storage.

Processing evaluations further demonstrate compatibility with FOWLP integration, including successful lamination, 5 µm via formation, and ultra-high-density planarized wiring at 2 µm line/space enabled by the incorporation of s sub-micron filler. Additional work is ongoing to expand process compatibility into other fabrication flows, including SAP.

V. Acknowledgment

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