Scalable Four-Layer Redistribution Layers via Fully Additive Build-Up: Demonstration of Defect-Free Multilayer Integration

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Abstract

The increasing complexity of heterogeneous integration and chiplet-based electronic systems is driving demand for multilayer redistribution layer (RDL) architectures with reliable lateral routing and vertical interconnection capability. However, increasing the number of RDL layers remains challenging due to cumulative surface topography, interfacial instability, layer-by-layer alignment complexity, and microvia integration challenges. In this work, we report the first four-layer RDL architecture fabricated using the fully additive Sequential Build-Up Covalent Bonded Metallization (SBU-CBM) process. The structure was fabricated on an FR-4 substrate and comprised four lateral copper redistribution layers interconnected by three staggered copper microvias embedded within five polyurethane dielectric layers. X-ray computed tomography (XCT) confirmed the successful formation of the four-layer architecture and the spatially distributed staggered microvia configuration. Optical and topographical analyses revealed progressive surface-topography accumulation with increasing RDL layer number, while the fabricated stack remained structurally stable with no visible delamination, edge separation, or large-scale deformation. This work represents the highest multilayer integration level achieved to date using the SBU-CBM process and establishes an important milestone toward fully additive multilayer RDL manufacturing for next-generation heterogeneous integration and chiplet-based electronic systems.

Key words

Multilayer redistribution layer (RDL), fully additive manufacturing, SBU-CBM process, staggered microvia

I. Introduction

The increasing adoption of heterogeneous integration and chiplet-based architecture is driving the demand for advanced redistribution layer (RDL) technologies capable of supporting high I/O density, high communication bandwidth, and complex package-level routing. Current RDL fabrication technologies are primarily based on subtractive and semi-additive processes (SAP/mSAP), which combine photolithography, electroplating, and etching to achieve fine-feature interconnect structures. Although these technologies have enabled advanced multilayer RDL platforms, increasing layer count introduces growing challenges associated with process complexity, material consumption, wafer warpage, layer-to-layer alignment, and interfacial reliability [1]. Additive manufacturing approaches have emerged as attractive alternatives due to their potential for simplified processing, reduced material waste, and improved manufacturing sustainability. However, existing printing-based approaches remain limited by feature resolution, conductor morphology, multilayer integration complexity, and the need for post-deposition thermal sintering [2]. The limitations of subtractive, semi-additive, and printing-based approaches indicate the need for an alternative RDL fabrication strategy that combines the process simplicity of additive manufacturing with the dimensional precision, interfacial robustness, and multilayer compatibility required for chiplet-based systems. In particular, such a method should enable selective copper formation without blanket seed-layer deposition or subtractive etching, avoid high-temperature sintering, provide strong metal–dielectric adhesion, and support reliable vertical interconnection through repeated build-up cycles. To address these requirements, the Sequential Build-Up Covalent Bonded Metallization (SBU-CBM) process has been developed at Luleå University of Technology as a fully additive metallization approach for miniaturized electronic interconnect fabrication. Unlike printing-based additive methods, SBU-CBM does not rely on nanoparticle inks or

post-deposition sintering. Instead, conductive copper structures are formed through selective surface activation and electroless metallization, where copper growth is confined to the patterned regions of the polymer surface at room temperature. This enables direct metallization of dielectric materials without conventional seed layers, vacuum deposition, or subtractive metal removal. The covalent bonding mechanism at the metal–polymer interface provides strong adhesion, which is particularly important for multilayer RDL architectures where repeated dielectric deposition, patterning, via formation, and metallization cycles can otherwise lead to interfacial degradation or delamination. The SBU-CBM method has emerged as a distinct fabrication route for advanced multilayer RDL architecture required in heterogeneous integration and chiplet-based systems. A key advantage of the SBU-CBM process is that high-resolution lateral interconnects and vertical microvia structures can be fabricated at room-temperature processing conditions. This characteristic reduces thermal stress, improves compatibility with wide range of organic substrates and polymer dielectrics, and avoids the substrate deformation and dimensional instability often associated with high-temperature sintering or repeated thermal processing. Furthermore, the maskless patterning capability of the process provides flexibility for rapid design iteration while maintaining the geometrical control required for miniaturized RDL structures. Previous demonstrations of SBU-CBM-based fabrication have shown its capability to realize complex copper interconnect geometries [3], including lateral interconnects with feature dimensions approaching 1 µm [4] and microvia structures below 10 µm [5]. Such capabilities are particularly attractive for advanced multilayer RDL architectures, where simultaneous scaling of lateral routing features and vertical interconnections is essential for achieving high-density package-level integration. In contrast to conventional RDL manufacturing approaches, the process combines lateral interconnect formation and vertical microvia integration within a sequential build-up framework, thereby reducing overall process complexity while maintaining a common fabrication route throughout the entire multilayer structure. The integration of laser-based patterning and microvia formation within a custom-built hybrid laser microfabrication platform further simplifies layer-to-layer registration and provides a practical route toward the realization of increasingly complex multilayer interconnect architectures. Since its introduction, SBU-CBM technology has undergone continuous development toward increasingly advanced multilayer interconnect architecture. Initial studies established the fundamental metallization mechanisms of the process and demonstrated its applicability for the additive fabrication of functional copper interconnect structures [3], [4]. Subsequent developments expanded the technology toward sequential multilayer build-up fabrication, establishing the technological foundation required for fully additive multilayer RDL manufacturing [5]–[7]. In this work, we report the first four-layer RDL architecture fabricated using the SBU-CBM process. This achievement represents a significant advancement in the evolution of SBU-CBM technology, extending its multilayer integration capability beyond previously reported demonstrations. The successful realization of a four-layer structure validates the continued scalability of the SBU-CBM method and demonstrates the ability of the process to maintain reliable multilayer integration over an increased number of fabrication cycles. As the highest multilayer integration level achieved to date using the SBU-CBM platform, this work constitutes an important technological milestone in the development of fully additive RDL manufacturing and provides an important foundation for the continued development of high-density multilayer RDL architectures targeting heterogeneous integration and chiplet-based systems.

II. Materials, Equipment, and Methods

A. Materials

FR-4 was used as the base substrate material and was purchased from Digi-Key Electronics Ltd. A UV-curable polyurethane (UV TP-1) and a photosensitive material (HP19) were supplied by Cuptronic AB (Stockholm, Sweden). Electroless copper deposition was carried out using PEC-660 series plating solutions obtained from J-KEM International (Stockholm, Sweden). All materials and chemicals were used as received without any additional purification or pre-treatment.

B. Equations

A Dymax ECE 5000 flood UV lamp curing system was used for curing the polyurethane layers. Planar patterning was performed using a gallium-nitride (GaN) laser writer (LW405B, MICROTECH, Italy) operating at a wavelength of 375 nm. Microvias were created using a PL2210-series diode-pumped picosecond (ps) Nd laser system. The system generated laser pulses at a wavelength of 266 nm with a pulse duration of 20 ps and a repetition rate of up to 2 kHz. Surface imaging of the fabricated samples was conducted using a Zeiss Axioscope 7 optical microscope. Three-dimensional structural characterization of the fabricated multilayer RDL architecture was performed using a Zeiss Xradia 620 Versa X-ray computed tomography (XCT) system at Luleå University of Technology (LTU). The measurements were carried out using a 20× objective with an X-ray source voltage of 80 kV and a source power of 10 W. An LE3 source filter was employed during acquisition, and the detector was

operated with a binning factor of 2. Projection images were acquired with an exposure time of 7 s per projection, and a total of 1601 projections were collected for tomographic reconstruction. The reconstructed volumetric dataset consisted of 963 × 974 × 999 voxels with an isotropic voxel size of 0.613 µm. The XCT analysis was used as a non-destructive characterization technique to investigate the internal three-dimensional architecture of the multilayer RDL structure, enabling visualization of the lateral copper interconnects, copper microvias, and layer-to-layer integration throughout the complete four-layer stack. Three-dimensional reconstruction, and image visualization were performed using the non-commercial version of Dragonfly software (Object Research Systems, Montreal, Canada).

C. Computer-Aided Design (CAD) and Mask Generation

To pattern the multilayer RDL architecture using the laser direct writing (LDW) system, a computer-aided design (CAD) mask was first created using the commercially available CLEWIN 5.0 software (WieWeb Software). The designed structure consisted of four lateral interconnect layers connected through three microvias. Each redistribution layer contained a single lateral interconnect line with dimensions of 300 µm in length and 50 µm in width. The microvias were incorporated at different lateral positions within the multilayer stack, resulting in a staggered interconnection architecture. In addition to the interconnect structures, fiducial alignment markers were integrated into the CAD layout to facilitate multilayer fabrication. The completed CAD mask was subsequently used for laser pattern generation during the sequential build-up process.

D. Fabrication Process

The four-layer RDL structure was fabricated using the SBU-CBM process through a sequential build-up strategy consisting of repeated dielectric deposition, lateral interconnect patterning and selective copper metallization, copper microvia formation steps. The final architecture consisted of four lateral copper lines embedded within five polyurethane dielectric layers and interconnected through three copper microvias positioned at different lateral coordinates within the stack. The fabrication process began with cleaning the FR-4 substrate using detergent, acetone, and ethanol in an ultrasonic bath, followed by rinsing with deionized (DI) water between each cleaning step. A layer of UV-curable polyurethane (PU) was then spin-coated onto the FR-4 substrate and cured under UV exposure for three minutes, forming the first dielectric layer (PU1). Subsequently, a photosensitive material (HP19) was spin-coated onto the PU1 surface. The first lateral interconnect pattern was defined using the LW405B laser writer. Following lateral pattern development and removal of unbonded photosensitive material, electroless copper deposition was carried out according to the supplier's instructions, resulting in selective metallization of the first lateral copper line (Cu Lin1). To establish vertical connectivity to the second redistribution layer, a second polyurethane layer (PU2) was deposited over Cu Lin1 and cured under UV illumination. Subsequently, the first microvia (mVia1) was formed using the PL2210 picosecond UV laser system. A photosensitive layer was then applied, and following selective photoactivation and electroless copper deposition, the microvia was metallized (Cu mVia1), thereby establishing a vertical electrical connection between the first and second redistribution layers. Subsequently, the second lateral interconnect was patterned using the LW405B system and selectively metallized through the SBU-CBM process. The fabrication sequence was continued by depositing a third polyurethane layer (PU3), followed by the formation and metallization of the second microvia. The third lateral copper interconnect was then patterned and metallized using the same procedure employed for the previous redistribution layers. Thereafter, a fourth polyurethane layer (PU4) was deposited, followed by the formation and metallization of the third microvia. The fourth lateral copper interconnect was subsequently patterned and metallized, completing the four-layer RDL architecture. Finally, a fifth polyurethane layer (PU5) was deposited to serve as the top dielectric layer of the structure. Throughout the build-up process, the three copper microvias were positioned at different lateral coordinates within successive layers, resulting in a staggered (zig-zag) vertical interconnection architecture. The completed structure therefore consisted of four copper redistribution layers (Cu Lin1–Cu Lin4) interconnected through three copper microvias (mVia1–mVia3) and embedded within five polyurethane dielectric layers (PU1–PU5). A schematic illustration of the fabrication sequence and the final multilayer architecture is presented in Fig. 1.

III. Results and Discussion

Fig. 2 presents photographs of the fabricated four-layer RDL structure after completion of the SBU-CBM fabrication process and subsequent imaging characterization. The red circles indicate the location of the embedded copper interconnect network within the multilayer structure. The successful fabrication of the sample without visible structural damage demonstrates the capability of the SBU-CBM process to support repeated dielectric build-up, metallization, and microvia integration steps required for multilayer RDL manufacturing. One of the principal challenges associated with increasing the number of redistribution layers is the progressive accumulation of mechanical stresses and interfacial instability throughout the multilayer stack. Repeated dielectric deposition, metallization, curing, and chemical processing steps can

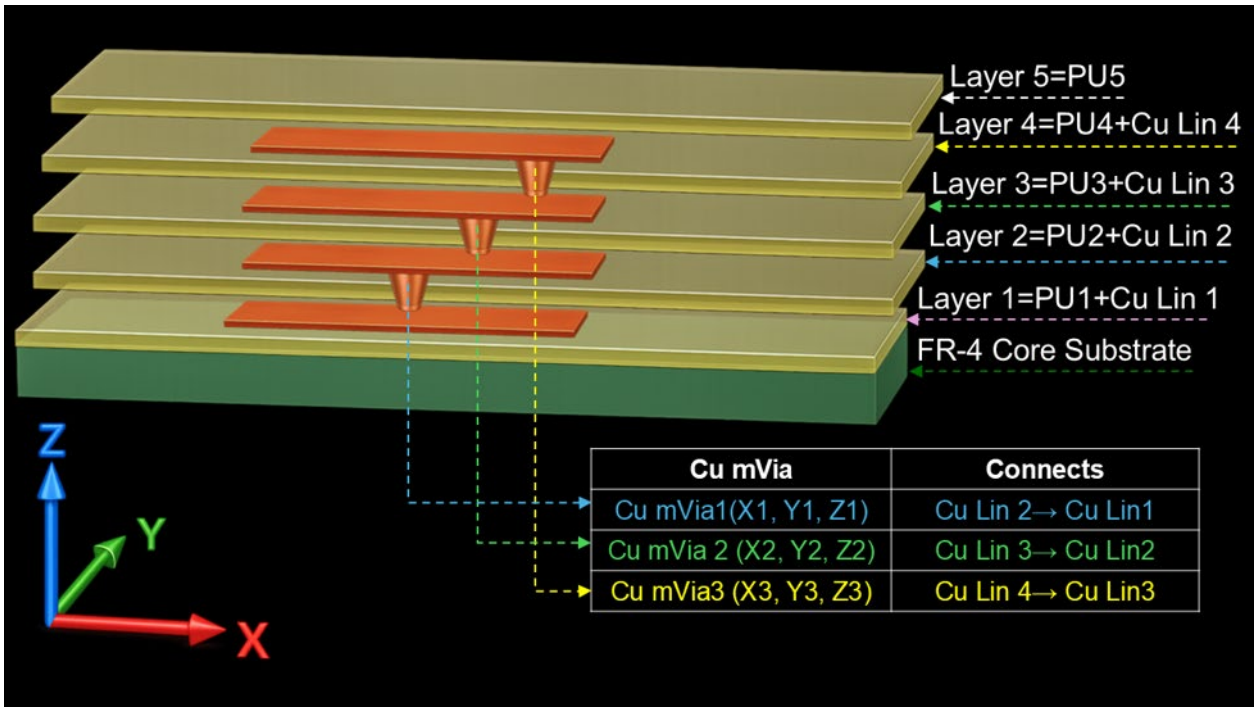


Fig. 1 Schematic illustration of the four-layer RDL architecture fabricated using the SBU-CBM process. The structure is built on an FR-4 substrate and consists of five polyurethane layers (PU1–PU5), four lateral copper lines (Cu Lin1–Cu Lin4), and three copper microvias (Cu mVia1–Cu mVia3). Layer 1 is composed of PU1 and Cu Lin1. Layer 2 is composed of PU2, Cu mVia1, and Cu Lin2. Layer 3 is composed of PU3, Cu mVia2, and Cu Lin3. Layer 4 is composed of PU4, Cu mVia3, and Cu Lin4. The final polyurethane layer (PU5) acts as the top dielectric/passivation layer. The three copper microvias are located at different lateral positions, schematically denoted as (X1, Y1, Z1), (X2, Y2, Z2), and (X3, Y3, Z3), forming a staggered zig-zag interconnection configuration rather than a centrally aligned vertical via stack.

promote interfacial degradation, resulting in delamination, cracking, edge separation, warpage, bending, and other structural defects. Such issues become increasingly pronounced as the number of build-up cycles increases and represent one of the major technological barriers to multilayer RDL scaling. As shown in Fig. 2, the fabricated four-layer structure exhibits excellent macroscopic structural integrity. No visible delamination, cracking, edge separation, or out-of-plane deformation can be observed. In particular, the side-view image shown in Fig. 2(b) reveals a well-preserved multilayer structure with no observable edge delamination or bending, which are among the most commonly encountered failure modes in multilayer RDL fabrication. Furthermore, the sample remained structurally stable after undergoing subsequent imaging characterization, including XCT analysis, with no visible evidence of mechanical degradation or interfacial failure. These observations indicate robust integration between the successive polyurethane and copper layers and provide strong evidence that the SBU-CBM process can support repeated multilayer build-up while maintaining the structural integrity of the RDL stack.

Fig. 3 presents XCT analysis of the fabricated four-layer RDL architecture. XCT was employed as a non-destructive characterization technique to investigate the internal structure of the multilayer stack and to evaluate the integrity of the redistribution layers and vertical interconnections following completion of the fabrication process. The reconstructed volumetric dataset enabled visualization of both the lateral copper interconnects and the embedded copper microvias throughout the multilayer structure.

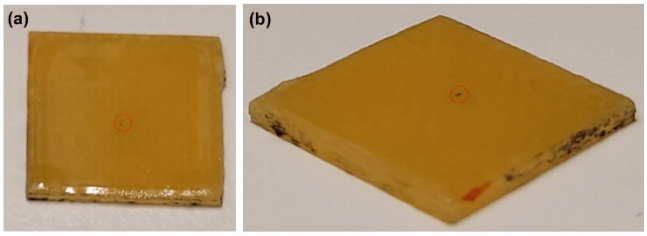


Fig. 2 Photographs of the fabricated four-layer RDL structure after completion of the SBU-CBM fabrication process and subsequent imaging characterization: (a) top view and (b) angled side view. The red circles indicate the location of the embedded copper interconnect network within the multilayer structure. No visible delamination, cracking, edge separation, or structural deformation is observed.

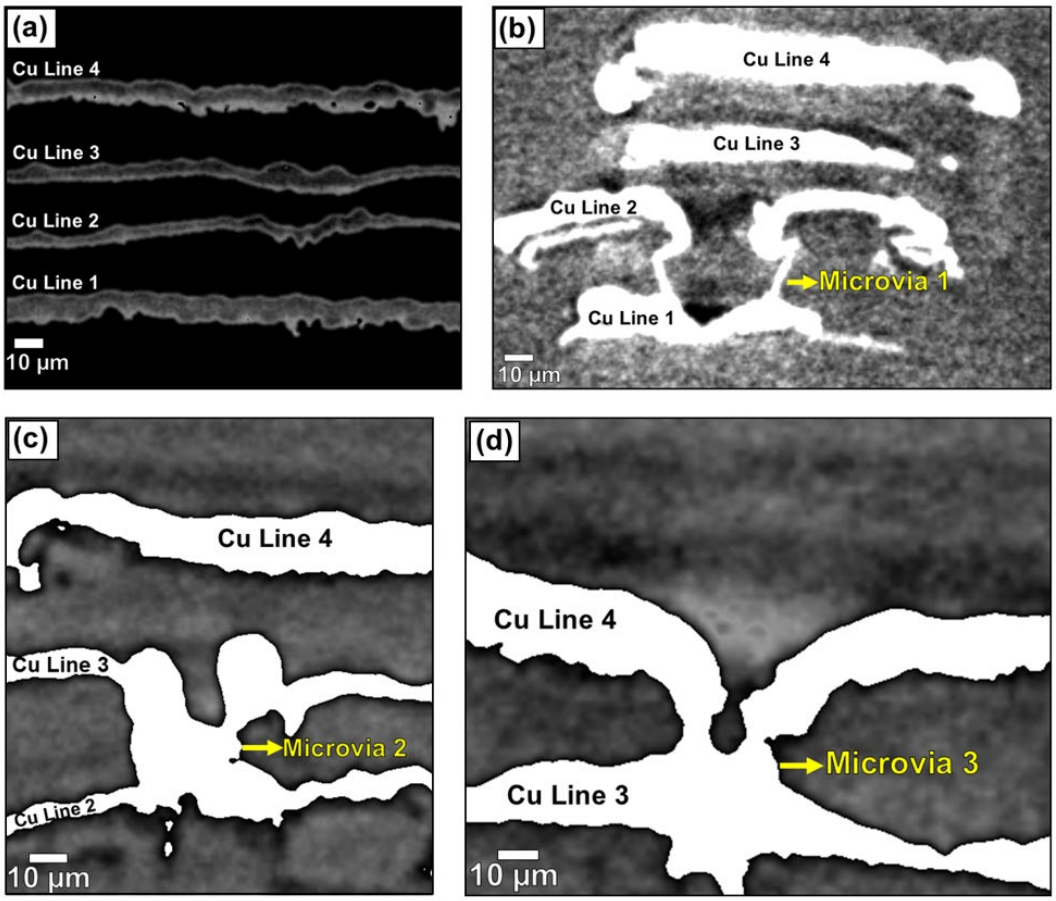


Fig. 3 XCT analysis of the fabricated four-layer RDL architecture using SBU-CBM process: (a) Representative cross-sectional XCT image extracted from slice 446/974 showing the complete multilayer structure. Four copper redistribution layers (Cu Lin1–Cu Lin4) can be clearly identified within the PU dielectric matrix, confirming successful layer-by-layer integration and preservation of the multilayer architecture. No microvias are visible in this slice because the cross-sectional plane does not intersect any of the staggered vertical interconnections; (b) XCT cross-sectional image extracted from slice 494/999 showing Microvia 1 (mVia1), which establishes vertical connectivity between Cu Lin1 and Cu Lin2; (c) XCT cross-sectional image extracted from slice 370/999 showing Microvia 2 (mVia2), which provides electrical interconnection between Cu Lin2 and Cu Lin3; (d) XCT cross-sectional image extracted from slice 324/999 showing Microvia 3 (mVia3), which connects Cu Lin3 and Cu Lin4. The three microvias are observed in different XCT slices because they are intentionally positioned at different lateral coordinates within the multilayer stack, forming a staggered vertical interconnection architecture rather than a vertically aligned via column.

A representative cross-sectional XCT image extracted from slice 446/974 is shown in Fig. 3(a). Four distinct copper redistribution layers can be clearly identified within the PU dielectric matrix, confirming the successful realization of the designed four-layer architecture. The copper layers remain well separated throughout the stack, and no evidence of delamination, layer collapse, or structural discontinuity is observed in the analyzed cross section. The preservation of multilayer architecture after multiple dielectric deposition cycles, metallization, and microvia fabrication steps provides strong structural evidence of successful layer-by-layer integration using the SBU-CBM process. It should be noted that no microvias are visible in Fig. 3(a), despite the presence of three vertical interconnections within the fabricated structure. This observation is expected because the image corresponds to a single cross-sectional slice through the reconstructed XCT volume [8]. Since the three microvias were intentionally positioned at different lateral coordinates to form a staggered interconnection architecture, none of the microvias intersect the specific cross-sectional plane represented in Fig. 3(a). Consequently, only the lateral copper interconnects are visible in this image. This behavior is commonly observed in XCT analysis of multilayer RDL structures containing staggered microvias, where different vertical interconnections appear in different cross-sectional slices depending on their spatial location within the reconstructed volume. The three copper microvias are shown individually in Figs. 3(b)–(d). Microvia 1, which connects

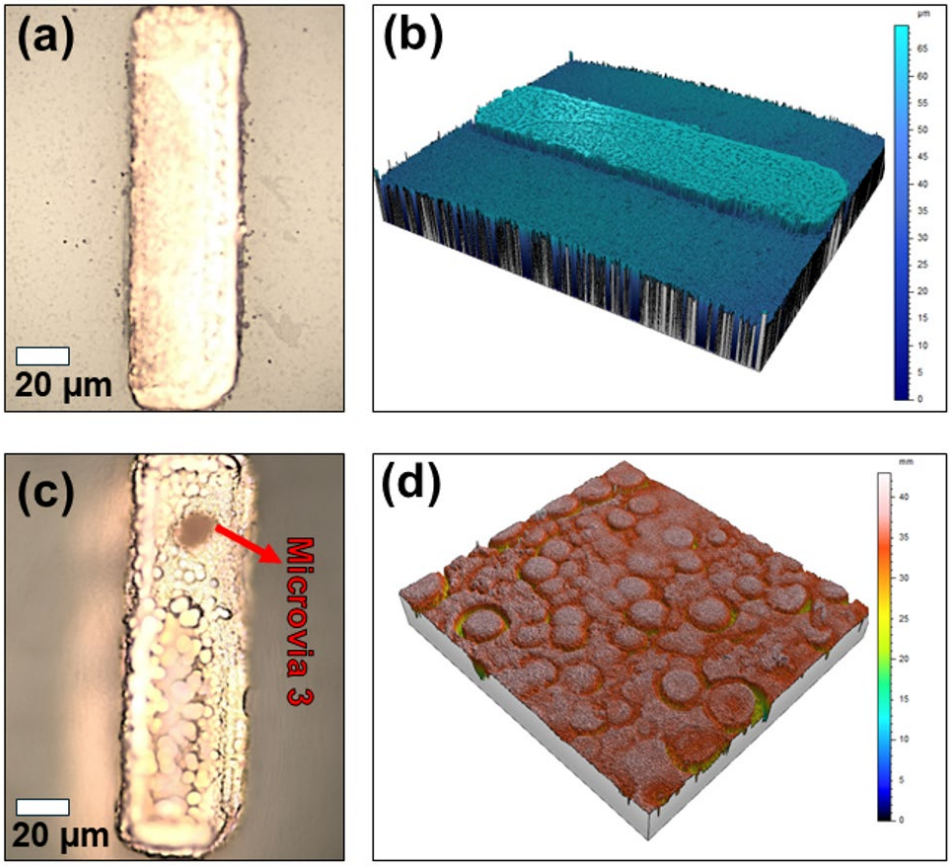


Fig. 4 Surface morphology and topographical characterization of the fabricated four-layer RDL architecture using SBU-CBM process; (a) Optical microscopy image of the first lateral copper line (Cu Lin1); (b) Corresponding three-dimensional surface topography visualization of Cu Lin1, showing a relatively smooth and uniform surface morphology; (c) Optical microscopy image of the fourth copper lateral copper line (Cu Lin4), with the location of Microvia 3 indicated; (d) Corresponding three-dimensional surface topography visualization of Cu Lin4, revealing increased surface-topography complexity and local height variations following successive dielectric deposition, microvia formation, and metallization cycles during multilayer build-up.

Cu Lin1 and Cu Lin2, is shown in Fig. 3(b) and is observed at slice 494/999. Microvia 2, which connects Cu Lin2 and Cu Lin3, is shown in Fig. 3(c) and is observed at slice 370/999. Microvia 3, which connects Cu Lin3 and Cu Lin4, is shown in Fig. 3(d) and is observed at slice 324/999. The three microvias are therefore not visible simultaneously within a single XCT cross-sectional image. This is a direct consequence of the staggered architecture employed in the present design, where each microvia is positioned at a different lateral coordinate within the multilayer stack. As a result, each vertical interconnection is intersected by a different XCT slice plane and appears at a different location within the reconstructed volume. This does not indicate structural discontinuity or an imaging artifact but rather confirms the spatial distribution of the microvias within the designed multilayer architecture. The XCT images further confirm vertical integration between adjacent redistribution layers. In each case, the microvia appears to establish a continuous connection between neighboring copper layers, demonstrating successful microvia formation and metallization throughout the sequential build-up process. The ability to realize three independent vertical interconnections distributed across different locations within the stack is particularly important for multilayer RDL architectures, where routing flexibility often requires microvias to be positioned at different lateral coordinates rather than in a single vertically aligned column. Taken together, the XCT results provide strong structural evidence for the successful fabrication of a four-layer fully additive RDL architecture incorporating four copper redistribution layers and three staggered copper microvias. The absence of observable large-scale delamination, together with the successful formation of all designed vertical interconnections, demonstrates the capability of the SBU-CBM process to support increasingly complex multilayer integration.

Fig. 4 compares the surface morphology of the first and fourth lateral copper lines within the fabricated four-layer

RDL architecture. Figs. 4(a) and 4(b) show the optical microscopy image and corresponding three-dimensional surface visualization of Cu Lin1, respectively. The first lateral copper line exhibits a relatively smooth and uniform surface morphology, indicating that the initial metallization step produced a comparatively flat lateral copper line during the early stage of the build-up process. In contrast, Figs. 4(c) and 4(d) show the optical microscopy image and corresponding three-dimensional surface visualization of Cu Lin4, which corresponds to the upper redistribution layer of the four-layer structure. Compared with Cu Lin1, Cu Lin4 exhibits a visibly rougher and more irregular surface morphology, with pronounced local height variations and nonuniform copper growth. The location of Microvia 3 is indicated in Fig. 4(c). This morphological difference indicates that surface topography progressively evolves during the sequential build-up process as additional dielectric deposition, microvia formation, and copper metallization cycles are introduced. The increase in surface topography with increasing RDL layer number is one of the major challenges in multilayer RDL fabrication [9]. Local surface nonuniformities generated in earlier processing steps can propagate into subsequent layers and may influence dielectric coverage, laser patterning, microvia formation, metallization uniformity, and layer-to-layer alignment. This issue becomes increasingly important as the number of redistribution layers increases, because each additional build-up cycle introduces further topographical and interfacial complexity. Although the upper copper layer exhibits increased surface roughness compared with the first copper layer, the four-layer RDL structure remained mechanically stable and structurally intact. No visible delamination, layer separation, or large-scale deformation was observed after fabrication and subsequent characterization. These results indicate that the SBU-CBM process can maintain multilayer structural integrity even in the presence of surface-topography accumulation, which is an important consideration for further development of higher-layer-count RDL architectures. The topographical images in Figs. 4(b) and 4(d) were used primarily for qualitative visualization of surface morphology; therefore, detailed quantitative roughness metrology is not discussed in this work and will be addressed in future process-optimization studies.

IV. Conclusion

In this work, a four-layer RDL architecture was successfully fabricated using the fully additive SBU-CBM process. The demonstrated structure comprised four lateral copper redistribution layers interconnected through three staggered copper microvias and embedded within five PU dielectric layers on an FR-4 substrate. This work represents the first demonstration of a four-layer RDL architecture realized using the SBU-CBM process and the highest multilayer integration level achieved to date with this technology. The successful fabrication of the four-layer structure demonstrates that the SBU-CBM process can be extended towards higher RDL layer counts while maintaining multilayer structural integrity and vertical interconnection capability. XCT analysis confirmed the formation of four distinct copper redistribution layers and three spatially distributed copper microvias arranged in a staggered configuration. Optical and topographical analyses showed progressive surface-topography accumulation with increasing RDL layer number, while the fabricated stack remained structurally stable with no visible delamination, edge separation, or large-scale deformation. This work establishes an important technological milestone in the evolution of the SBU-CBM platform, demonstrating its continued scalability toward increasingly complex multilayer RDL architectures for heterogeneous integration and chiplet-based systems.

From a cost-benefit perspective, the fully additive SBU-CBM approach offers several potential advantages over conventional subtractive and semi-additive RDL fabrication, including reduced material consumption by avoiding blanket metal deposition and etching, maskless patterning that facilitates rapid design changes, and room-temperature copper metallization that reduces the thermal processing burden. In addition, lateral interconnect and microvia formation can be integrated within the same sequential build-up framework, potentially reducing process complexity for multilayer structures. These benefits are particularly relevant for prototyping and customized multilayer RDL fabrication. However, the present approach still involves relatively time-consuming laser direct writing for larger patterned areas and requires specialized laser equipment, representing important considerations for manufacturing throughput and initial equipment investment. Therefore, further process optimization and scaling are required to establish the cost advantage for high-volume manufacturing.

Future work will focus on electrical characterization of the fabricated RDL structures, including lateral line resistance, microvia continuity, and vertical interconnect performance. In addition, detailed quantitative surface analysis and process optimization will be required to control roughness variation, improve dielectric planarization, and enable reliable extension toward higher-layer-count RDL architectures for heterogeneous integration and chiplet-based electronic systems.

Acknowledgment

The authors gratefully acknowledge the generous support of Cuptronic AB (Stockholm), whose provision of specialized materials was essential to the successful completion of this

research. Sincere thanks are also extended to Fredrik Forsberg and Henrik Lycksam for their expert assistance with XCT imaging, which was instrumental in validating the multilayer structures. The authors further wish to express their deep gratitude to Claudio Arnone and Jithin Thomas at MICROTECH-Italy for their invaluable guidance and technical support during the installation and operation of the LW405B laser writing machine. The authors also acknowledge the computational support provided by the Swedish National Infrastructure for Computing (SNIC), with resources provided through projects NAISS 2025/23-632 and NAISS 2026/3-207, which enabled the modeling and analysis activities conducted in this study. This work is supported by the E2PACKMAN project. This project has received funding from Chips Joint Undertaking (JU) under grant agreement No 101194187. The JU receives support from the European Union's Horizon Europe research and innovation program and Germany, Austria, Belgium, Finland, France, Israel, Italy, Netherlands, Portugal, Romania, Slovakia, Sweden, and Türkiye. In addition, the consortium receives national funding from Germany, Austria, Belgium, Finland, Israel, Italy, Netherlands, Portugal, Romania, Slovakia, Sweden, and Türkiye. Additional support is acknowledged from the SOPRANO project, funded by the Interreg Aurora Foundation.



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