# Sub-Micron Patterning & High-Aspect-Ratio Structures in Advanced Substrates with Dry Etching and Liquid Metal Ink Metallization

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## Abstract

The growing demand for Panel Level Packaging to meet the needs of High-Performance Computing (HPC), Artificial Intelligence (AI) and advanced chiplet architecture requires a scalable solution for ultra-high-density and high-signal integrity interconnects. Ajinomoto Build-up Film (ABF) is a proven dielectric material in advanced packaging due to its low dielectric loss and fine-pitch compatibilities, enabling reliable ultra-dense pattern formation and high-performance device integration.

While laser via formation is a conventional approach for ABF processing, its sequential nature makes it slow and challenging to scale to a cost-effective panel-level process. In addition, it suffers from thermal damage effects and debris accumulation, making it challenging to achieve ultra-small features. These limitations create bottlenecks in high-density interconnect fabrication, impacting throughput, cost, and signal integrity.

By contrast, dry etching offers a more controlled and precise batch-process alternative, eliminating the need for chemical desmear, and enabling better feature profile definition, significantly higher aspect ratios, and minimal residue and thermal damage. This study explores the use of different hard mask materials for ABF dry etching and examines the impact of etching parameters on feature profile and selectivity. While photoresist masks struggle to achieve small feature diameters and high aspect ratios, the optimized dry etching process with metal hard masks in our study successfully achieved sub-1µm features with 10:1 aspect ratios. Additionally, Laser Direct Imaging (LDI) was utilized to create precise patterning, demonstrating a flexible and scalable method for high-density pattern fabrication in advanced panel-level packaging.

Following structure formation, the application of a novel Liquid Metal Ink deposition process was evaluated, demonstrating a scalable, reliable, and cost-effective method of fine-resolution copper metallization in advanced Panel Level Packaging applications. LMI compatibility with Epoxy Mold Compounds (EMC) was also evaluated. Fine-line patterning is demonstrated on EMC and RDL materials to assess the feasibility of the Liquid Metal Ink approach for high-density interconnects in Fan-Out Wafer Level Packaging (FOWLP) applications.

## Key words

Build-up film, dry plasma etching, interconnect formation, Liquid Metal Ink, panel-level packaging

## I. Introduction

The rapid development of high-performance computing (HPC), artificial intelligence (AI), and 5G has pushed packaging technologies to deliver higher signal speed, lower power consumption, and increased input/output (I/O) density. To meet these requirements, advanced substrate materials and interconnect architectures are evolving rapidly. One of the key challenges in this area is the formation of high-density interconnects with tight dimensional control and minimal defects. As interconnect scaling advances, there is a growing demand for fine via and trench features.

In these applications, Ajinomoto Build-up Film (ABF) is widely used in the build-up layers of package substrates due to its favorable electrical properties, thermal stability, and compatibility with semi-additive processes. However, its composite structure, which includes both resin and silica fillers, presents challenges for patterning, especially at fine feature scales. The formation of fine-pitch features in ABF remains difficult due to the differing etch behaviors of its organic and inorganic components. Conventional methods such as laser drilling are inherently sequential, which limits throughput and makes them less suitable for high-volume manufacturing. In addition, laser-based processing often results in debris formation, sidewall roughness, and high taper angles due to uneven energy absorption in the resin-filler system. These taper angles not only degrade signal quality but also limit the achievable feature depth, making it difficult to realize high-aspect-ratio structures [1].

Reactive ion etching (RIE), particularly in the form of deep reactive ion etching (DRIE), has emerged as a promising alternative for forming fine features in ABF. Compared to laser drilling, RIE offers better control over etch profiles, reduced sidewall damage, and the ability to achieve high-aspect-ratio structures through anisotropic etching. Several studies have demonstrated the feasibility of using RIE to form vertical vias and trenches in ABF with improved process uniformity and reduced residue [2][3]. A key consideration in dry etching is the choice of masking material. While photoresist masks are simple to apply and remove, they often suffer from limited etch resistance and deformation when targeting deep or narrow features, especially in the sub-5 µm range [4]. To address these limitations, metal hard masks are frequently used to improve etch selectivity and dimensional accuracy. These masks are typically patterned using dry film resist (DFR) and laser direct imaging (LDI), offering better stability during long plasma exposures. Recent work has also explored lift-off strategies and non-wet mask removal techniques to further streamline the process flow and avoid damage to underlying layers [5].

In this work, we demonstrate patterning and formation of fine structures of dimension ≤ 1 µm on ABF layers by dry etching using RIE and metal hard masks. Different mask materials are compared, and the impact of etching parameters on trench profile and selectivity is examined. Specifically, photoresist and LDI are used for mask patterning. The plasma etch process enables the formation of ABF features ranging from 0.6 to 1 µm in width, achieving aspect ratios up to 10. These results validate the feasibility of forming straight trenches on ABF down to 0.6 µm with AR up to 10 by dry plasma etch using metal hard masks.

To support fine-feature metallization on dielectric substrates, we introduce a simplified, non-vacuum seed layer process based on Liquid Metal Ink (LMI$^{TM}$), developed by LQDX. This Atomic Seed Metallization chemistry enables ultra-thin, pinhole-free, and conformal Pd deposition on complex surfaces. Unlike conventional PVD-based methods, LMI is scalable, cost-effective, and compatible with organic packaging materials. In this work, LMI was applied to dry-etched ABF trenches as narrow as 5 µm, followed by electroless copper plating. The process demonstrated uniform and conformal copper coverage inside the trenches, validating the compatibility of LMI with ABF topographies the capability for fine-line metallization in advanced packaging applications.

In addition to ABF, the LMI process was also applied to a Sumitomo epoxy mold compound (EMC) substrate, followed by electroless copper plating and photolithographic patterning using dry film resist and LDI. These results demonstrate the feasibility of integrating LMI-based seed layers into fine-feature patterning workflows on rough organic surfaces. This lays the groundwork for a complete metallization process—including electrolytic copper plating, photoresist stripping, and seed layer etching—without the need for vacuum-based techniques, further highlighting the process flexibility across different organic substrate types.

## II. Experiments

### *A. Hard Mask Material Selection*

There are two critical requirements for the mask material: (1) high resistance to fluorine-based plasmas, which are widely used for ABF etching, and (2) the ability to be

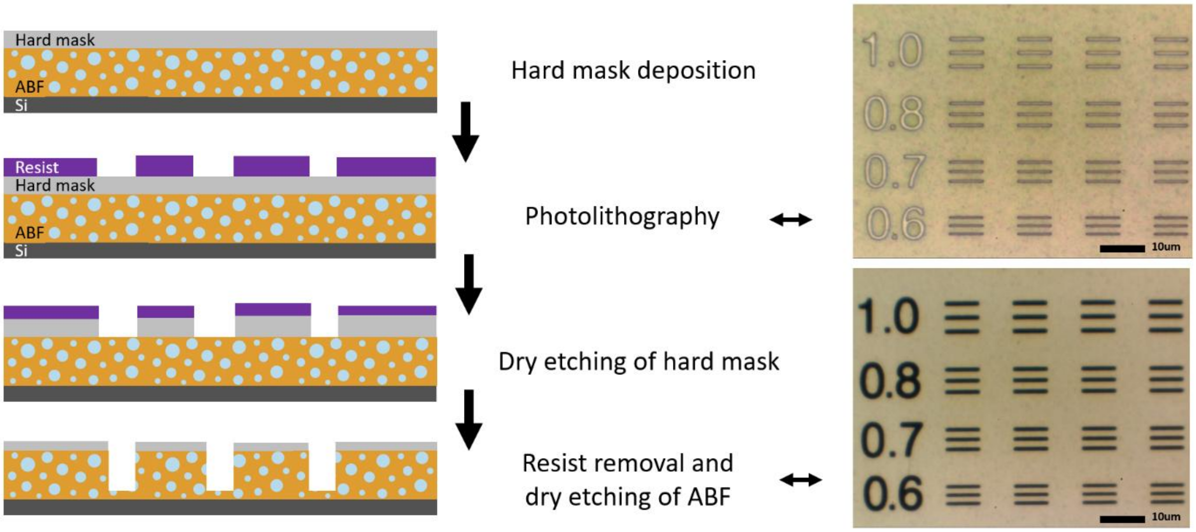

*Figure 1. Process flow and related optical microscope images. Unit of the numbers: um.*

patterned by dry etching methods without relying on wet processes. Cu has been used as a hard mask material in several studies due to its availability and process compatibility with panel-level tools [5-7]. However, patterning Cu typically requires wet etching, which is isotropic and can lead to undercutting. This not only limits dimensional control but also introduces risks such as delamination and reduced adhesion between the ABF and the underlying substrate due to chemical interaction and moisture absorption during wet processing. These limitations make Cu less favorable for fine-pitch and high-aspect-ratio features, especially in applications requiring high reliability. For these reasons, Cr and Ni, which are both compatible with dry etching, were selected for experimental comparison in this work.

### *B. ABF Etching Process*

The process flow is shown in Fig.1. A 25 µm thick GL-102 ABF layer laminated on a silicon wafer was used as the base for all samples. The Cu layer served as a conductive landing layer but was not involved in mask patterning. To evaluate hard mask materials for dry etching, 500nm thick Cr and Ni were deposited by physical vapor deposition (PVD) using a Lesker sputter system. Both metals were selected for their good dry etch compatibility and high resistance to fluorine-based plasmas, as discussed in previous studies.

After metal deposition, a ~1 µm layer of AZ3312 positive photoresist was spin-coated and soft-baked. Mask patterning was performed using an LDI system—specifically, a Heidelberg MLA-150 operating at a 405 nm wavelength. This technique enabled high-resolution pattern transfer onto the resist layer. After exposure, the resist was developed in an aqueous solution, revealing the pattern for hard mask etching.

The hard mask was then etched using a PlasmaLab M80 Plus RIE system, followed by $O_2$ plasma ashing to remove the remaining photoresist. Subsequently, ABF etching was carried out in a PlasmaTherm RIE 790 system using fluorine-based plasma. Rather than relying on fixed recipes, a series of etch conditions were tested to identify optimal parameters for anisotropy, profile control, and selectivity. The goal was to explore the influence of gas composition and pressure on feature shape and depth. These optimizations were essential to achieve vertical sidewalls and high aspect ratios under certain conditions. Initial results under non-ideal conditions often showed Si0$_2$ filler residues on sidewalls, which were addressed through iterative process adjustments.

### *C. LMI Metallization on ABF and EMC*

LMI metallization was performed on both ABF and EMC substrates. For ABF, the process was applied to samples with 5 µm-wide trenches formed by dry etching using the optimized plasma recipe. After surface preparation, a Pd-based LMI solution was coated and cured, followed by electroless copper plating at about 70 nm to form a conformal seed layer within the etched features. On the EMC side, the same LMI formulation was coated and cured on a Sumitomo mold compound substrate, followed by electroless copper deposition. Dry film photoresist (ADH158) was laminated, exposed using the Heidelberg MLA-150 system at 375 nm, and developed to define fine-line patterns on the Cu-seeded surface. These steps demonstrated successful integration of LMI with standard photolithographic workflows on rough organic materials. Further steps, including electrolytic copper plating, photoresist stripping, and palladium removal, are planned as part of complete metallization flow development.

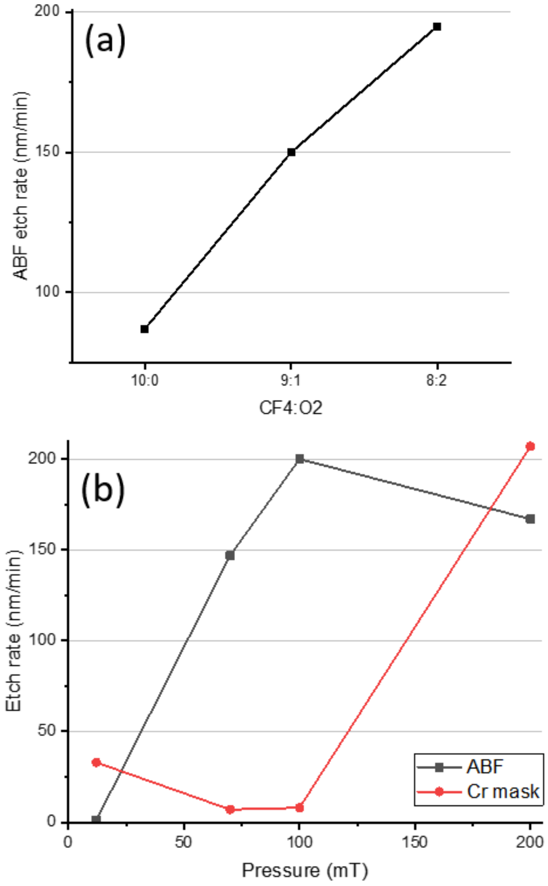

*Figure 2. (a) ABF etch rate at different gas ratios. (b) Etch rates of ABF and Cr mask at different chamber pressures.*

## III. Results and Discussion

### *A. Evaluation of Cr and Ni Metal Masks*

The performance of Ni and Cr as metal hard masks for ABF etching was evaluated in terms of etch resistance, selectivity, and compatibility with fine-feature patterning. Both materials demonstrated sufficient resistance to fluorine-based plasma used in ABF reactive ion etching. However,

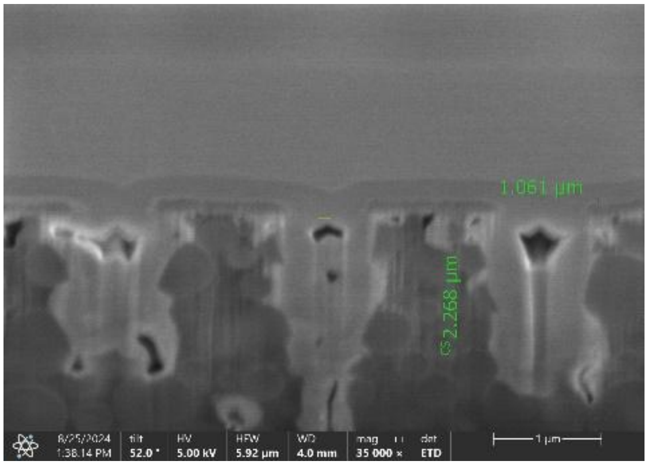

*Figure 3. $SiO_2$ filler residues on sidewalls with unoptimized recipe. The trench is filled with protection deposition for cross-sectional imaging.*

notable differences were observed in their overall process behavior.

Nickel exhibited excellent resistance to fluorine chemistry, with an etch selectivity to ABF greater than 30. While this high selectivity is beneficial for maintaining mask integrity during prolonged ABF etching, Ni showed poor selectivity to photoresist under chlorine-based plasma, with values below 0.3. This low selectivity leads to rapid photoresist erosion during the mask etch step. To compensate, a thicker photoresist layer is required to fully transfer the pattern into the Ni mask, which compromises lithographic resolution and makes it more difficult to achieve narrow linewidths or high aspect ratios. As a result, Ni masks are not well-suited for fine-feature or high-aspect-ratio applications, especially when using standard LDI tools and positive-tone resists.

In contrast, chromium exhibited slightly lower selectivity to ABF, with values above 20, but provided much better compatibility with photoresist patterning. The Cr-to-photoresist selectivity exceeded 2 under Chlorine-based etching conditions, enabling more stable resist profiles during mask transfer. This makes Cr a more favorable choice for fine-pitch and high-aspect-ratio structures, where control over both mask integrity and resist profile is essential. Based on these observations, Cr was selected for further optimization and process development.

### *B. Etching Parameters Optimization*

To identify optimal conditions for ABF etching with Cr hard masks, two key process parameters were evaluated: gas composition ($CF_4$:$O_2$ ratio) and chamber pressure. The goal was to maximize the ABF etch rate while maintaining good mask integrity and ensuring process compatibility for fine-feature transfer.

#### *1) Gas composition: $CF_4$:$O_2$ ratio and Ar addition*

As shown in Figure 2(a), the ABF etch rate increases with the introduction of $O_2$ into the $CF_4$ plasma, due to enhanced oxidation of the epoxy resin phase. However, despite the higher etch rates achieved at a $CF_4$:$O_2$ ratio of 8:2, we observed significant sidewall contamination in the form of residual $SiO_2$ filler particles, which is shown in Fig. 3. This is attributed to the mismatch in etching behavior between the organic resin and the inorganic filler components of ABF.

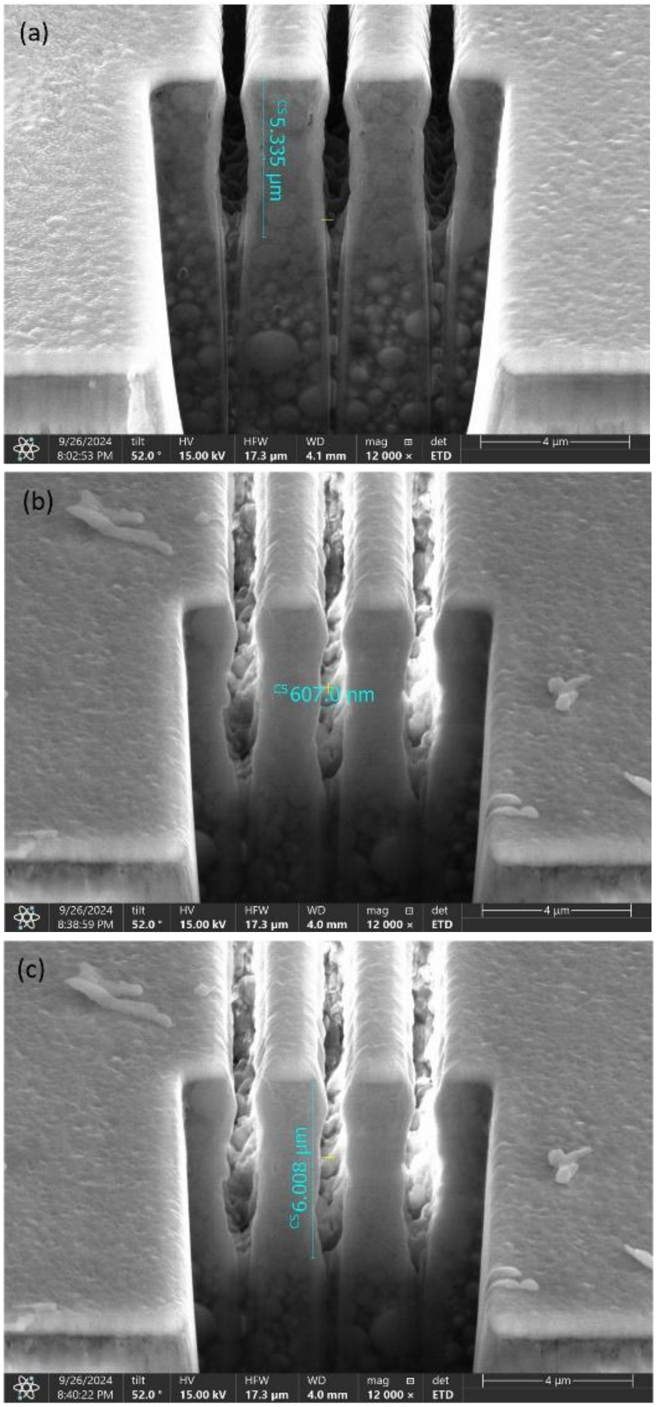

*Figure 4. Cross-sectional images of (a) 0.7 µm-wide trenches etched to a depth of 5 µm (b)(c) 0.6 µm-wide trenches with an etch depth of 6 µm*

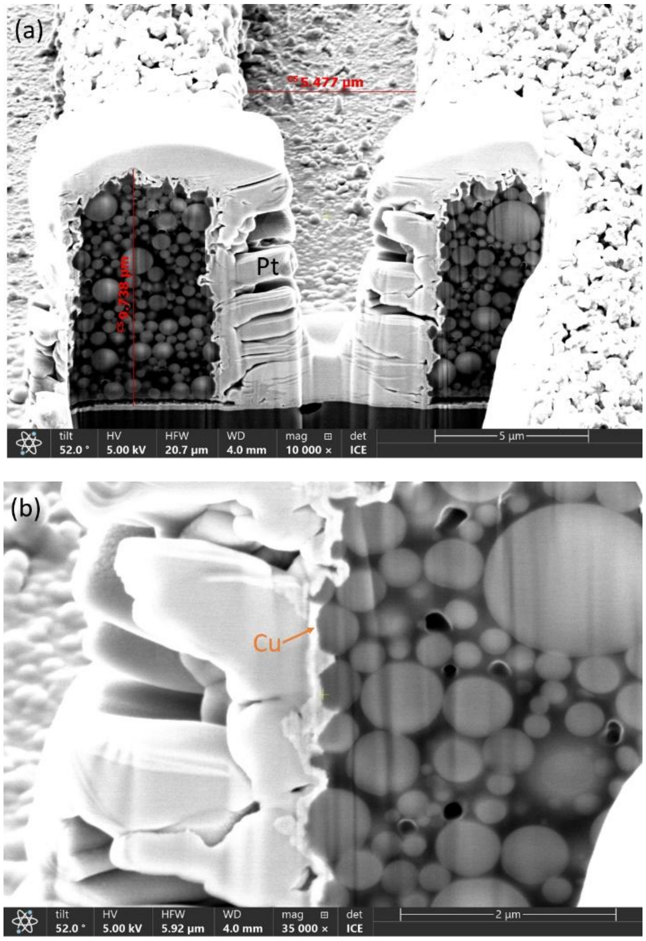

*Figure 5. Cross-sectional images of LMI and electroless plated Cu in 5um-wide ABF trenches. The copper layer conforms to the trench sidewalls and bottom, enabling uniform deposition without voids.*

To address this, Ar was added to the gas mixture to introduce a physical sputtering component. The Ar ions helped dislodge residual filler material from the sidewalls, improving profile cleanliness without substantially reducing the ABF etch rate. While $CF_4$:$O_2$ = 8:2 remained the chemical baseline, the addition of Ar proved essential for achieving acceptable sidewall quality in fine-feature applications.
This optimized gas composition, with controlled $O_2$ content and Ar addition, was used in subsequent pressure studies to further improve etch selectivity and feature integrity.

*2) Chamber pressure: influence on etch rate and selectivity*

Chamber pressure was varied under the optimized gas composition ($CF_4$:$O_2$ = 8:2 with Ar) to assess its impact on etch behavior. As pressure increased, ABF etch rate initially improved; however, a sharp rise in Cr mask erosion was observed beyond a certain point, resulting in a significant drop in selectivity, as shown in Fig.2 (b).

One possible explanation is that at higher pressures, the reduced mean free path increases ion-neutral collisions, which broadens the angular distribution of ion bombardment. This reduces etch directionality and may enhance lateral sputtering of the Cr mask, leading to accelerated erosion.

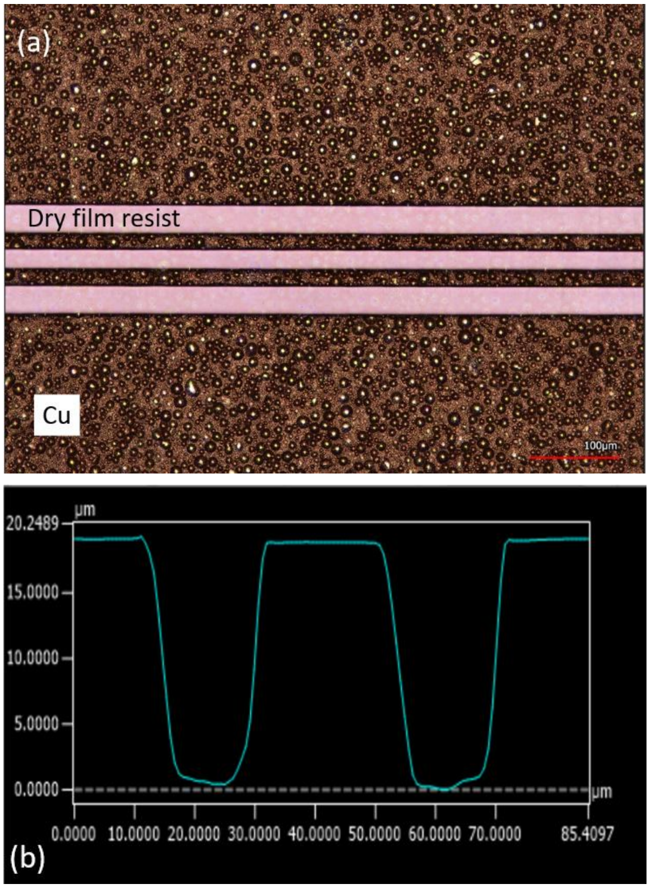

*Figure 6. (a) Laser + optical image of 15um L/S pattern on electroless Cu plated EMC (b) Topography measurement by laser microscope*

Based on these results, a pressure of 100 mT was selected for the final etch recipe. It offered a balance between high ABF etch rate and minimal Cr loss, ensuring sufficient selectivity and stability for pattern transfer in fine-feature applications.

### *D. Sub-Micron Patterning & High-Aspect-Ratio Features in ABF*

To evaluate the effect of the optimized etching conditions on feature quality, cross-sectional SEM imaging was performed on ABF samples patterned using Cr hard masks. The samples were etched using the final recipe: $CF_4$:$O_2$ = 8:2 with Ar addition at a chamber pressure of 100 mT. Under these conditions, Fig. 4 shows the etched features exhibited vertical sidewalls with reduced surface roughness. Residual silica filler particles observed in earlier trials were no longer present, indicating that the addition of Ar effectively enhanced sidewall cleaning. A maximum aspect ratio of 10:1 was achieved, corresponding to 0.6 µm-wide features etched to a depth of 6 µm. The Cr mask remained intact throughout the process, with clear pattern transfer, supporting earlier conclusions regarding its selectivity and stability.

It is worth noting that the ABF used in this study was of the GL type, which contains relatively large $SiO_2$ filler particles. In future work, nano-filler ABF will be explored to enable finer topography and smoother sidewalls in submicron via and trench structures.

### *E. Metallization on ABF and Mold Compound Using LMI™ Process*

Palladium-based LMI was coated into 5 µm-wide ABF trenches, followed by electroless Cu plating. Fig. 5 presents cross-sectional SEM images of an ABF trench after metallization. Pt was deposit during cross-sectional milling to protect the Cu and LMI. The Cu layer and LMI attached to ABF show good conformality and coverage along both the sidewalls and trench bottom. These results validate the integration of non-vacuum metallization into the ABF process flow and highlight the potential of the LMI approach for fine-feature copper interconnects in advanced packaging applications.

On the Cu-seeded EMC surface, 15 µm line and space features were successfully patterned using nearly 20 µm-thick dry film photoresist, which is shown in Fig. 6. This was achieved after optimizing lithography parameters including resist lamination, exposure dose, and development conditions. The underlying EMC substrate exhibited a surface roughness (Sa) of approximately 3 µm, which is known to limit resolution due to scattering and resist thickness variation. Despite this challenge, the resist profile showed good definition, demonstrating the capability of the LMI-based process to support fine-feature patterning on rough organic surfaces.

## IV. Summary

In summary, this study demonstrated the feasibility of fabricating fine features on ABF using optimized dry etching with metal hard masks. By systematically evaluating mask materials, gas composition, and chamber pressure, we achieved well-defined trench structures with aspect ratios up to 10:1 and minimum feature sizes down to 0.6 µm. The etched profiles showed vertical sidewalls and reduced residue, validating the effectiveness of the optimized process. A non-vacuum metallization process using LMI™ was then applied to dry-etched ABF trenches, successfully forming conformal copper seed layers within 5 µm features. In parallel, the LMI process was also demonstrated on EMC to assess its broader applicability. These results support the development of high-density copper interconnects on organic substrates for advanced fan-out and panel-level packaging.

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