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Novel Low Temperature Curable Photo-Patternable Low Dk/Df for Wafer Level Packaging (WLP)

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***Abstract*— As the 5G technology roll out continues, next generation dielectric layer materials are a major component of device packaging designs. The challenge is designing a material that provides a balance of characteristics to withstand the harsh environments and complex designs of the devices. Most importantly, the stability of the material is imperative to the performance of the packaged device. The next generation materials require a low dielectric loss (Df), low dielectric constant (Dk), and low moisture absorption whilst attaining the good mechanical and thermal properties to resist the inherent stresses in the final package. Additionally, emerging materials must be competitively priced and/or offer ease of manufacturability in order to offset current industry players and overcome the complexity of assembly. A novel low temperature curable, photo-patternable low Dk and low Df dielectric material is presented. PRL-29 offers a robust balance of characteristic properties that prove material stability and high reliability in simulated 5G conditions.**

Keywords—Polymer Dielectric, Dissipation Factor, High Frequency, Wafer Level Packaging, Photosensitive

I. INTRODUCTION

The 5G technology surge is impacting several key system technologies: cellular communications, autonomous vehicles and advanced driver assistance systems (ADAS), internet of things (IoT), massive multiple input, multiple output (MIMO), and cognitive radio. One of the major challenges of 5G technology is finding a dielectric material that can provide stability and high reliability for the complexity of next generation devices at high frequencies. An ideal material will be stable over a range of frequency, temperature, and moisture levels. Designing dielectric materials that are capable of withstanding high frequencies requires a low dielectric constant and more importantly a low dissipation factor over a range of frequencies. Further, a low dielectric constant sustaining over a range of temperatures proves the performance and endurance of the material under severe conditions. A low dissipation factor means less energy will be lost as higher frequency waves pass through the material increasing reliability. Percent water uptake is another important aspect in material engineering. Water has a high dielectric constant of 80. Thus, humidity and moisture can have major effects on the stability of a dielectric layer at high frequencies if sensitive to moisture absorption. Trade-off between cost efficiency and processability can be made based on application, engineered design, and capabilities of the manufacturer. The dielectric material needs to factor in external stresses such as copper bonding and CTE mismatches. It is necessary to design new and emerging dielectric materials with manufacturability in mind [1-3]. The 5G technology environment is moving quickly and with the ADAS and autonomous vehicle surge, millimeter-wave (mmWave) sensors require higher frequency standards than RF and microwave circuits. The automobile industry is already using materials with low dielectric losses at 77 GHz for radar PCB antennas to improve automotive electronic safety systems. Soon automotive and other mmWave industries will be looking for dielectric materials with low losses up to 110GHz [4-7]. With the emphasis on engineering a material with low Dk and low Df, the inherent mechanical and thermal properties of the material must still be well balanced. In application, reducing stress of a redistribution layer (RDL) dielectric is crucial for the reliability endurance of the final package. Any distortion due to heating or humidity can become a major issue, ultimately resulting in stress induced failure from material cracking and delamination. The dielectric material must have strong mechanical and thermal properties with the ability of being cured at lower temperatures, less than 225°C, to avoid added stresses. [8-10]

We present a novel, negative-tone dielectric material for wafer level packaging applications in emerging mmWave 5G technology. PRL-29 offers key features such as stable, low Dk

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(2.5) and low Df (0.004) up to 85GHz, and minimal moisture absorption (<0.04%). Additionally, PRL-29 has standard processing capabilities and compatibility with industry standard fab developer solvents and can be cured at low temperatures below 225°C achieving high resolution.

II. MATERIALS AND METHODS

A. *Innovative Polymer Design*

Kayaku Advanced Materials and Nippon Kayaku have jointly synthesized a novel block co-polymer and formulation sensitive to photo curing. This unique material is referred to as PRL-29 and exhibited in Figure 1. PRL-29 is a negative tone resist that can be applied as a photo-patternable layer with post cure thickness of up to 15μm with low temperature curing capability below 225°C.

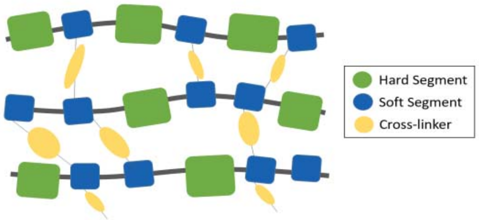


Fig. 1. PRL-29 Structure

B. *Lithography Process*

Samples were prepared in clean, UV protected glass containers between 25mL and 300mL. Formulation constituents were added to the glass container then rolled for at least one hour to fully homogenize the solution. Samples were then filtered through at least 0.5μm polypropylene glycol membrane. Formulated samples were then spun-coated onto 6" silicon wafers between 700RPM to 1200RPM to achieve desired film thickness between 10μm and 20μm. Immediately after coat, wafers were soft-baked then exposed under broad-band, hard contact exposure tool between 50mJ/cm^2 – 200mJ/cm^2 forming a latent image in the dielectric layer. Wafers were then post exposure baked at the desired temperature and finally solvent developed in PGMEA (Figure 2). This system requires a peak temperature cure of 200°C for 1 hour to enable full cross-linkage through self-polymerization of the resin.

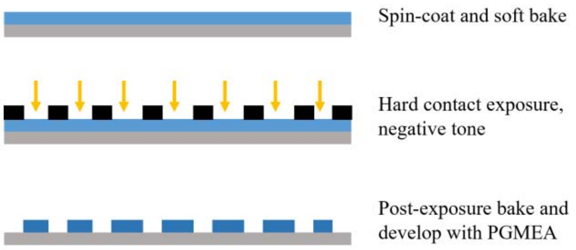


Fig. 2. PRL-29 photolithography process flow.

C. *Characterization Methods*

Thermomechanical testing was performed by creating free-standing films of the resist with dimensions of 10mm in width by 50mm in length. Samples were pulled on an Instron with a pull-rate of 50mm/min. The glass transition temperature was measured on TA Instruments DMA 850. Electrical testing was performed by resonant cavity method for 1-20GHz and free space method for 70-85GHz. The coefficient of thermal expansion was measured by Mettler-Toledo TMA/SDTA 841e. Water uptake samples were measured in 24-hour deionized water immersion test at 23°C as well as 85°C and 85% relative humidity for 120 hours. Pressure cooker testing was performed under 121°C at 100% relative humidity, 2 atmosphere for 48 hours. Shear adhesion testing pre and post PCT testing on silicon substrate was measured on the DAGE 4000 series. Bias HAST testing was performed under 85°C and 85% relative humidity for 168 hours with biasing at 3.3 volts.

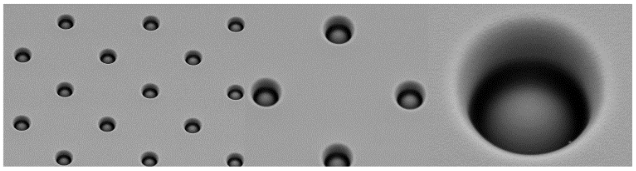
III. RESULTS AND DISCUSSION

A critical part of designing a dielectric material is measuring the essential properties for real-world application. Even if lithographic performance is excellent, the material must provide the necessary thermal, mechanical, and electrical properties to survive harsh device environments.

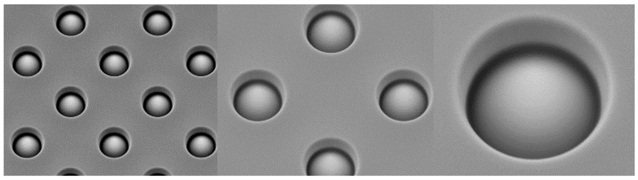
A. *Lithography Performance*

PRL-29 can achieve via patterning at aspect ratios close to 1 at a 15μm film thickness. Process modifications are still not optimized which demonstrates the potential capabilities of this dielectric material based on what we have already achieved. Figure 3 shows SEM images of PRL-29 15μm and 20μm vias at a 15μm film thickness.

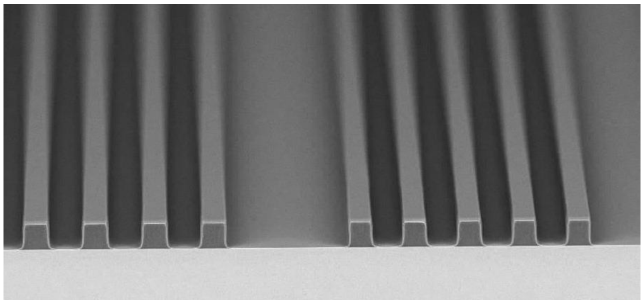
(a) 15μm vias | 15 μm film thickness



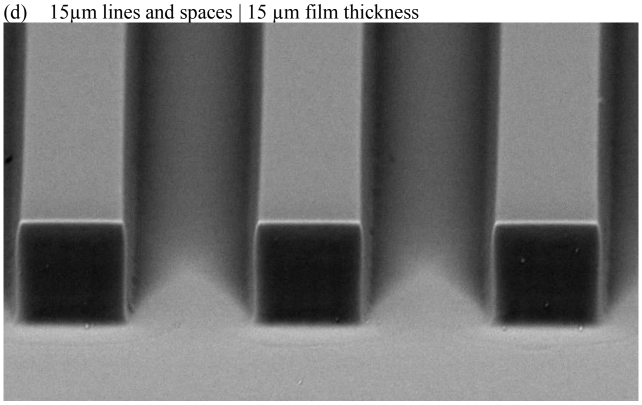
(b) 20μm vias | 15 μm film thickness



(c) 15μm lines and spaces | 15 μm film thickness



(d) 15µm lines and spaces | 15 µm film thickness



(e) 15µm lines and spaces | 15 µm film thickness

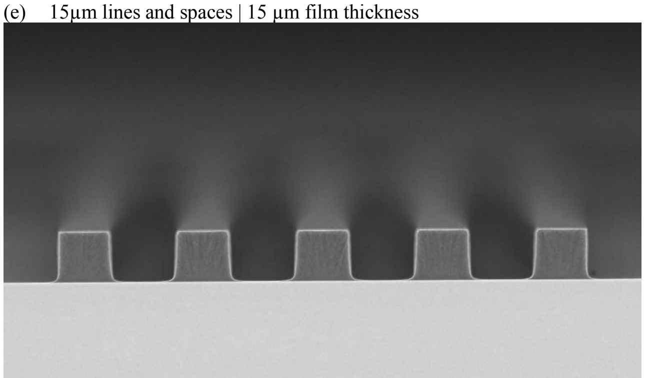


Fig. 3. (a) – (b) PRL-29 via resolution. (c) – (e) PRL-29 line and space resolution.

B. *Material Characteristics*

With a lower cure temperature at 200°C for one hour, PRL-29 compares well to other standard industry materials such as polyimide material curing at temperatures above 300°C. In a true device setting and environment, the dielectric material will experience intrinsic stresses. Thermomechanical properties such as high elongation and low modulus are essential for material endurance and performance. PRL-29 has an elongation value of 35% and Young's modulus of 1.8 GPa, respectively (Figure 4). The glass transition temperature (Tg) of PRL-29 is roughly 220°C (Figure 5). Table 1 summarizes PRL-29 characteristics.

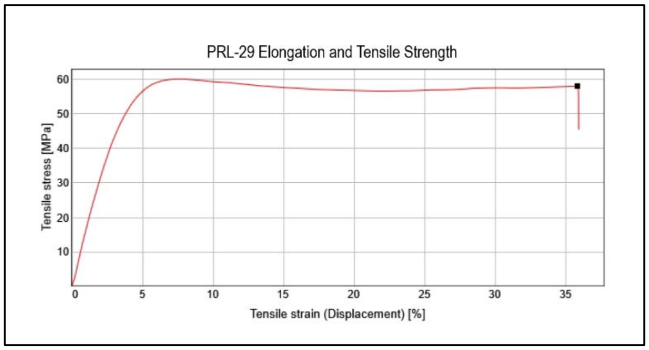


Fig. 4. Stress versus strain curve of PRL-29 thin film samples pulled on Instron. Sample size was around 10mm width, 50mm length, and 13µm thickness. Pull rate was 50mm/min.

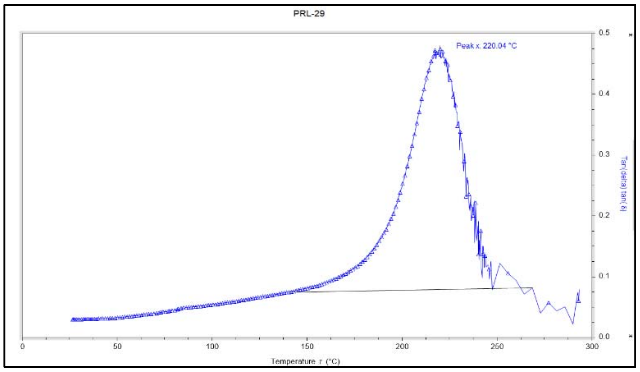


Fig. 5. Glass transition temperature of PRL-29 measured.

TABLE 1. PRL-29 PROPERTIES

PRL-29 Properties		
ITEM	***UNITS***	***VALUE***
Cure Temperature	°C	200
Aspect Ratio		1:1
Tg	°C	220
Young's Modulus	GPa	1.8
Tensile Strength	MPa	60
Elongation at Break (max) 10mm x 50mm, 50mm/min	%	35
CTE α1 (< Tg)	ppm/°C	62
Shear Adhesion (Si)	MPa	35
Shear Adhesion post PCT (Si)	MPa	33
Dielectric Constant	1-85 GHz	2.5
Dissipation Factor	1-85 GHz	0.004
Water Absorbance 85°C/85%RH, 120hr	%	0.3
Water Absorbance 23°C, 24-hour immersion	%	0.03
Thermal Conductivity (-25°C to 150°C)	W/m/K	0.23
PCT 121°C/100%RH, 48hr		Pass
Bias HAST 85°C/85%RH, 3.3V, 168hrs		Pass
Chemical Resistance		Excellent

With the 5G technology surge, the dielectric properties of a material are key characteristics of performance in the RF, microwave, and mmWave frequencies. The stability of the material's dielectric constant and dissipation factor over a wide range of frequencies determines the durability and more importantly, the application range of the material. From 1 to 10 GHz, film sample sizes were 3mm by 80mm and about 100µm thick. At 20 GHz film samples sizes were 40mm by 40mm and about 50µm thick. For 70 to 85GHz, a large film sample was prepped at 4mm by 4mm with an average thickness of 1.5mm. PRL-29 proves to be a stable dielectric insulator with a dielectric constant of around 2.5 and a dissipation factor of around 0.004 from 1 GHz all the way to 85 GHz. Table 2 summarizes the dielectric data and Figure 6 graphs the dielectric constant and dissipation factor (loss) over 20GHz to 85GHz frequencies. This demonstrates the potential for PRL-29 to be applicable in next generation automotive electronic circuits.

TABLE 2. DIELECTRIC SUMMARY DATA

Frequency	Dielectric Constant (Dk)	Dissipation Factor (Df)
1 GHz	2.63	0.005
10 GHz	2.54	0.004
20 GHz	2.48	0.004
70 GHz	2.49	0.004
75 GHz	2.48	0.004
80 GHz	2.48	0.001
85 GHz	2.49	0.003

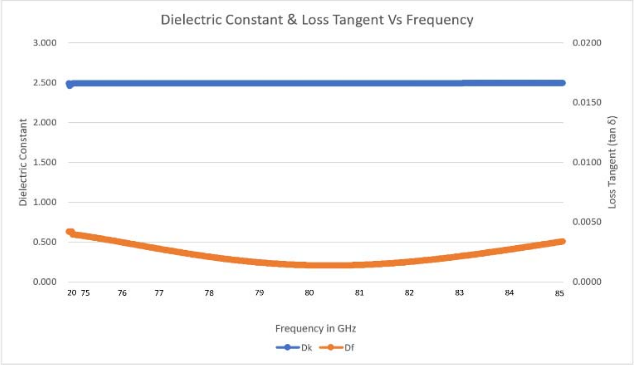


Fig. 6. Dielectric Constant and Loss Tangent versus Frequency.

C. *Chemical Resistance*

The dielectric material will undergo a series of stripping and etching steps during the manufacturing process of a WLP device. It is crucial for the RDL to not only withstand but be stable during these processing steps where some require system heating. The chemical resistance of PRL-29 was tested and results summarized in Table 3 show no degradation in film loss or appearance. PRL-29 was coated on silicon substrate, patterned, developed, and cured for chemical resistance inspection. 15µm posts, 20µm vias, and 40µm vias were inspected under optical microscope for change in appearance while bulk areas were measured for change in film loss. PRL-29 film was tested in a subset of acids and alkaline chemicals: N-Methyl-2pyrrolidone (NMP), Dimethyl sulfoxide (DMSO), Acetone, Sulfuric Acid (H_2SO_4), Buffered oxide etch (BOE), and Tetramethylammonium hydroxide (TMAH).

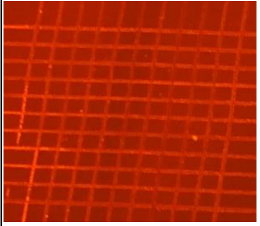
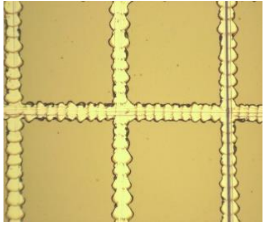
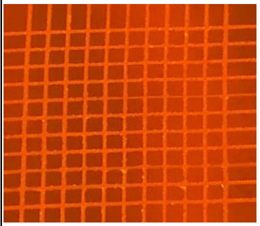
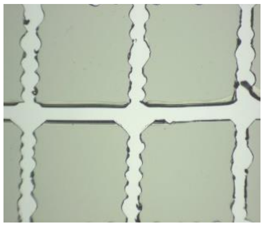
TABLE 3. CHEMICAL RESISTANCE TESTING

Chemical Resistance of PRL-29				
Chemicals	Treatment Condition		Check Item	Exposure Dose and Cure Temperature
				200°C for 60 minutes
	Temperature (°C)	Time (minutes)		100 mJ/cm^2
NMP	80	60	Appearance	Ok
			Film Loss	No
DMSO	90	60	Appearance	Ok
			Film Loss	No
Acetone	25	60	Appearance	Ok
			Film Loss	No
10% H_2SO_4	25	15	Appearance	Ok
			Film Loss	No
2.38% TMAH	25	15	Appearance	Ok
			Film Loss	No
BOE (6:1 NH_4F:HF)	25	60	Appearance	Ok
			Film Loss	No

D. *Reliability*

Reliability testing is crucial to simulate extreme end-use application environments. PRL-29 was evaluated for adhesion testing on silicon and copper substrates before and after pressure cooker testing (PCT). Bare silicon and copper wafers were coated with PRL-29 and processed accordingly. Crosshatch tape peel testing was performed before PCT and after PCT at 121°C and 100% relative humidity for 48 hours. PRL-29 passed PCT on both silicon and copper substrates and post PCT top-down images are shown in Table 4. Shear adhesion was performed on silicon substrate with a value of 35 before PCT and 33 after PCT. This negligible change in shear adhesion shows how PRL-29 does not exhibit any delamination or failure during PCT. Shear adhesion to copper will be evaluated in future work.

TABLE 4. PRESSURE COOKER TEST

Pressure Cooker Test: **121°C 100% Relative Humidity, 2 atmospheric pressure, 48 hours**		
Copper		
Silicon		

The stability of a polymer's modulus over temperature is essential to understand the material's crystallinity and ability to endure harsh conditions whether at extremely high or low temperatures. PRL-29 was tested alongside KMRD and a commercial epoxy product to correlate the temperature cycling test (TCT) performance over a broad temperature range. In previous studies, KMRD has proven to pass TCT for 2000 cycles. In contrast, epoxy polymers are notorious for their brittleness and inability to sustain harsh conditions. Figure 7 plots Young's Modulus over a temperature range from -55°C to 125°C. As shown, PRL-29 and KMRD exhibit similar linear relationships of modulus versus temperature while the epoxy product shows significant instability over temperature. Further, PRL-29 displays a lower Young's modulus than KMRD suggesting that the material is soft and indicates lower stresses with increased strain. PRL-29 and KMRD both show slight increase in modulus at low temperatures compared to ambient. From ambient to high temperatures, PRL-29 and KMRD only slightly change in modulus. This is encouraging for future temperature cycling performance of PRL-29 at 1000 and 2000 cycles planned in future work.

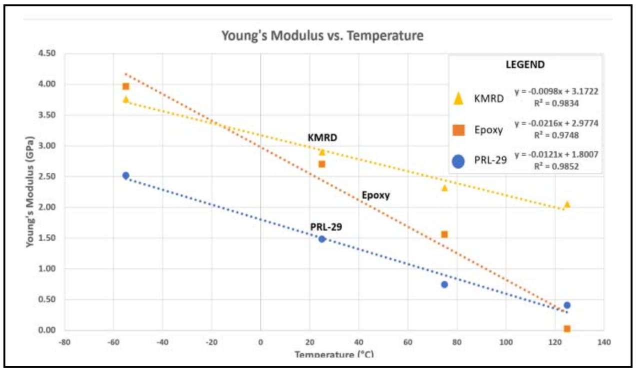


Fig. 7. Young's Modulus versus temperature comparison of PRL-29, KMRD, and Epoxy materials.

In order to understand the insulation capacity of PRL-29, bias HAST (bHAST) testing was performed at 85°C and 85% relative humidity for 168 hours with applied biasing at 3.3 volts. Device structures were assembled on 6" silicon wafer substrates. PRL-29 was coated on the silicon wafer at around a 10μm film thickness. Titanium and copper at 200 Å and 2000 Å were deposited on top of the coated wafers. Metal deposited wafers were then plated with copper structures based on specific bHAST design depicted in Figure 8. The titanium and copper seed layer were etched and PRL-29 was spun-coated as the insulative top layer. Copper wires were soldered onto the open pads connecting to 5μm lines and spaces pattern. A cross section of the final device structure is represented in Figure 9. The resistance was monitored over time to observe any device shorting due to copper migration. Figure 10 shows the results of resistance over time during bHAST. The 5μm copper lines and space structures insulated by PRL-29 show no evidence of copper migration throughout the testing proving that PRL-29 is a good, insulative material under harsh conditions (Figure 11).

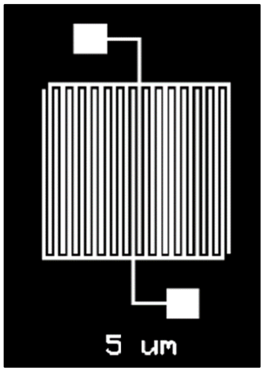


Fig. 8. Bias HAST device design for 5μm lines and spaces.

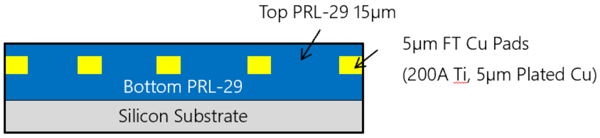


Fig. 9. Cross section schematic of final bias HAST device structure

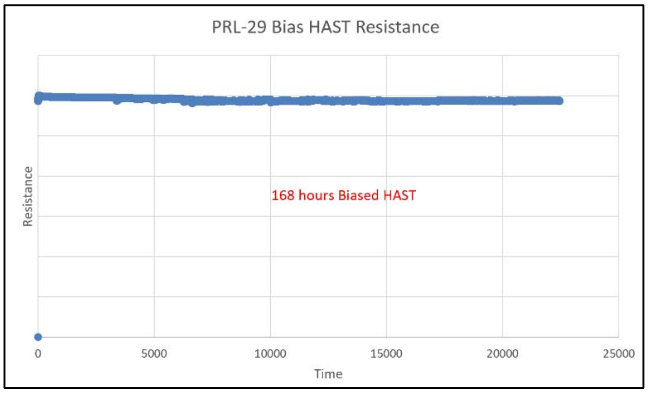


Fig. 10. Bias HAST resistance over 168 hours.

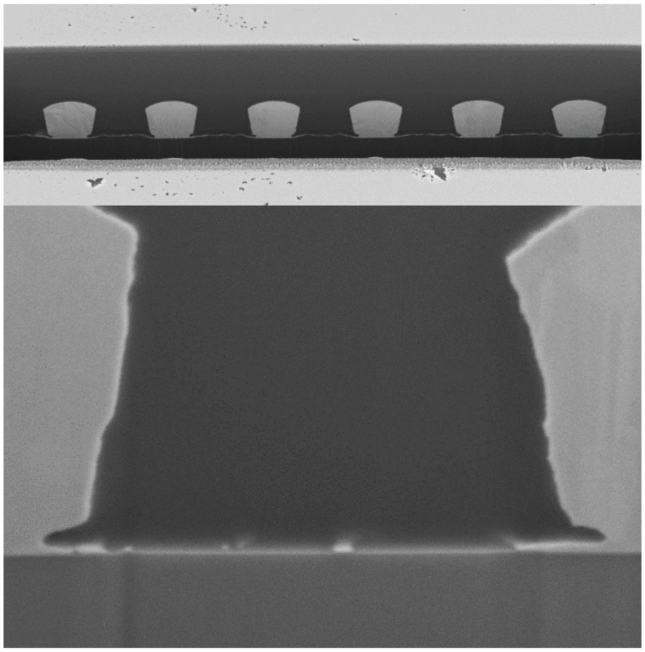


Fig. 11. Cross section of insulated copper pillars after Bias HAST.

IV. CONCLUSION

As 5G infrastructure ascends, the stakes are higher, and specifications tighter. In order to build a robust system, a well-balanced and stable dielectric material is paramount to achieving mmWave technologies. We have presented PRL-29, a novel low loss photodielectric, that has advantageous attributes in processability, dielectrics, thermal, and mechanical properties. PRL-29 shows promising, desirable characteristics suitable for achieving 5G next generation packages.

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