FLEXIBILITY MATTERS: HIGH PURITY, THIN, FLEXIBLE ALUMINA RIBBON CERAMIC

***Corning first showcased this material at the 2019 Ceramic Expo.*

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Device manufacturers need innovative new materials to develop smarter, faster, and smaller next-generation electronic devices. Corning has invented a new generation of high-performance ceramic substrates in entirely new form factors that can help solve customer problems.

We demonstrate a unique process able to make high-purity, thin, continuous ceramic ribbons with a dense and fine microstructure. The thin form factor enables fast sintering rates. Across a broad composition space, materials such as zirconia, alumina, and silica can be produced.

In this paper, we introduce a high-performance alumina ribbon ceramic (>99.9 % pure, 1.4 µm fine grains, thin, flexible, and large area) and outline the ceramic's key properties; we also discuss process capabilities demonstrated on this new form factor. This product advances electronic devices with low loss, good heat management, and size miniaturization in high speed data communication (e.g., 5G/mmWave, THz), which is especially essential in unconventional curved or conformal design. The thin ceramic substrate supports nonepitaxial thin film growth, in which a sapphire-like attribute is required as well as large size, thinness, and low manufacturing cost.

FLEXIBLE ALUMINA?

If any material is thin enough, it can be flexible. But to be useful in high-tech manufacturing, ultrathin materials need to remain durable and stable in processing and end use. It's a tough problem, and Corning solved it with ceramics thin enough to be spooled on a roll.

Manufacturing of thin ceramics is very difficult due to the challenge of suitable shape control. Traditionally, thin ceramics are fabricated through a costly conventional polishing approach, which limits achievable thicknesses and wafer size. Therefore, identifying a cost-effective process capable of producing high-purity, ultrathin ceramics with good shape control would be a significant innovation for thin sheet technical ceramics.

Corning developed a novel fast sintering process, in which a continuous formed green tape is conveyed through a sintering furnace in a continuous fashion to form a continuous sintered ceramic ribbon. It is a high-temperature, short-time sintering approach, which is possible because thin ceramics can tolerate rapid heating and cooling rates. For example, compared to conventional sintering cycles, which may take many hours or even days, the new firing cycle lasts only minutes.

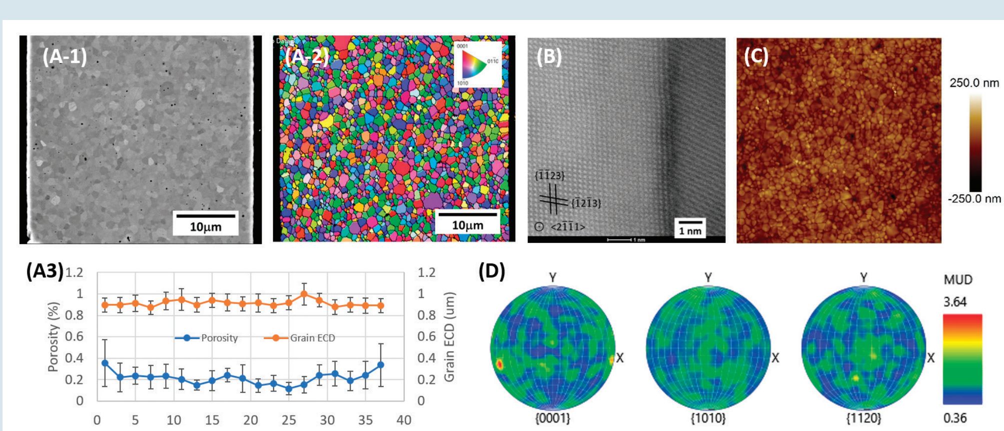

Figure 1. Microstructure of alumina ribbon ceramic. (A) SEM on grain size, porosity; (B) TEM on grain boundary; (C) Atomic force microscopy on surface roughness; (D) Pole figures on grain orientation.
Credit: Corning, Inc.

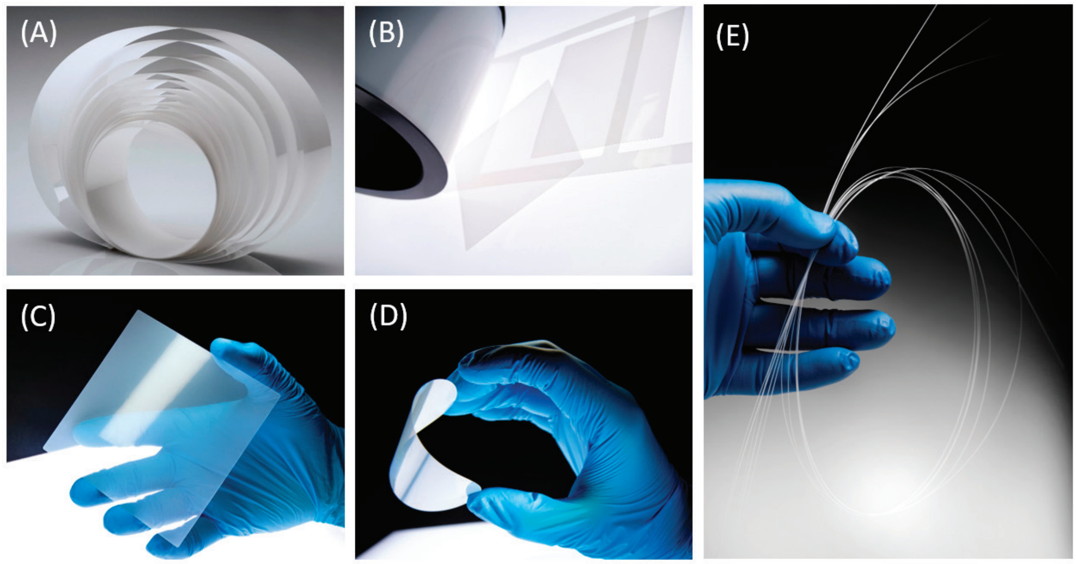

Figure 2. Different form factors of ultrathin alumina ribbon ceramic. (A-B) roll form, (C-D) sheet form/panel, and wafer (E) "cable" form/long narrow strips. *Credit: Corning, Inc.*

This novel sintering process enables several attractive product attributes, including low manufacturing cost and long lengths. Widths of up to 100 mm of spooled alumina were demonstrated for spools up to about 100 m long, and it is potentially scalable to 200 mm or 300 mm width to meet size requirements for most semiconductor wafer processes. Thickness is limited by bend stress and ranges from 20–100 μm for alumina.

MICROSTRUCTURE

Compared to conventional sintering, our process favors densification over grain growth in alumina, where high-temperature/short-time sintering enables dense and fine grain microstructures.[1–3]

Figure 1 shows microstructural data collected on the dense and fine-grained features of an alumina ribbon ceramic sample. Image analysis on the cross-sectional electron backscattering diffraction image gives a grain size of about 1.4 μm and SEM porosity of less than 0.4% at pore size of about 190 nm (> 99 % dense), which is also distributed uniformly along the thickness (Figure 1A). Transmission electron microscopy reveals clean grain boundaries with no apparent amorphous film or segregation of impurities (Figure 1B).

As a result of the fine grain, native surface roughness, Ra, retains at 30–50 nm (Figure 1C). This level surface roughness is between typical smooth surface (like glass) and rough surface (like PCB), thus favoring copper adhesion and also enabling fine line structure in metallization processes. Therefore, it should be sufficient for most application cases. Further requirements on surface smoothness (a few nanometers or even less for thin film devices) could be achieved through electropolishing or planarization. Pole figures in Figure 1D proves randomly oriented grain growth and uniform grain size distribution.

FORM FACTORS

Alumina ribbon ceramic is produced in rolls (Figure 2A) and supplied as panels or wafers with appropriate cutting (Figure 2B) either through laser or mechanical saw cutting. Figure 2C and 2D show the two most widely used geometries: 100 mm x 100 mm square panels and 100 mm diameter round wafers. The capability of alternative form factors, such as meter-long narrow ribbons, are demonstrated in Figure 2E. This format is unique to thin ribbon ceramics and could be very useful for applications requiring thin, long, and flexible substrates, such as dielec-

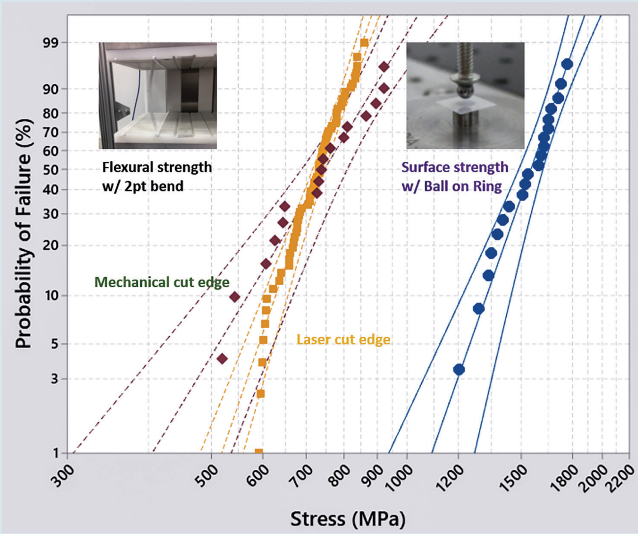

Figure 3. Surface strength with ball on ring test (blue) and flexural strength with two-point bend (laser edge [yellow] and mechanical cut edge [red]) on 40 μmt alumina ribbon ceramic. *Credit: Corning, Inc.*

tric waveguides and harsh environment sensors. The example in Figure 2E is a 1 m long strand that is 40 μm thick and 0.5 mm wide. Until now, a long-length, flexible, high-purity alumina ribbon ceramic form factor was not attainable.

MECHANICAL PROPERTIES

Benefiting from a dense and fine grain microstructure, alumina ribbon ceramic exhibits a high surface strength and edge strength, which could potentially make handling the material easier and less prone to breaking compared to conventionally ground thin-sheet ceramic. Characterizing mechanical properties on thin substrates could be challenging as the sample is too thin and flexible for conventional three- or four-point bend testing. Instead, we combined a ball-on-ring test for surface strength[4] and two-point bend test for flexural strength[5] on 40 μm alumina ribbon ceramic.

The ball-on-ring test[4] provides an "intrinsic" type surface strength measurement while surveying a very small test area, and the two-point bend test is better for evaluating process and handling flaws as it tests

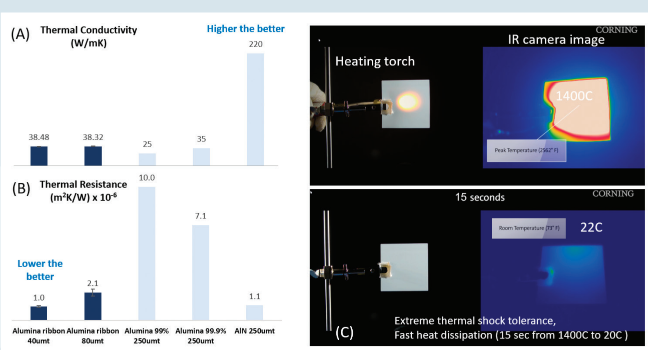

Figure 4. (A-B) Thermal conductivity and thermal resistance comparison between alumina ribbon ceramic, conventional sheet alumina, and alumina nitride; (C) Illustration of thermal shock tolerance and heat dissipation on 40 μmt alumina ribbon ceramic with a torch experiment.
Credit: Corning, Inc.

a larger area. Figure 3 shows Weibull plots of probability of failure against applied stress in these two different test configurations. A test set with 3 mm diameter stainless steel ball, 4 mm diameter support ring, and 8 mm x 8 mm sample was used for the ball-on-ring test at 1.2 mm/min test speed. The surface strength resulted in a Weibull B10 (10% of probability of failure) of about 1.3 GPa, corresponding to maximum flaw dimension of about 6 μm.

For two-point bend on flexural strength, two sets of samples cut with laser and mechanical saws were tested. While a Weibull B10 of about 600 MPa (and average bend strength of 720 MPa) on laser trimmed edges revealed in the plot indicates edge flaws impact strength, this strength is superior to conventional ground thin-sheet alumina (~400 MPa). Mechanically cut edges show strength about equal to laser trimmed edges with a somewhat wider distribution, indicating alumina ribbon ceramic could accommodate a conventional die cut process.

THERMAL PROPERTIES

Many applications take advantage of alumina's good thermal properties. The thermal conductivity of Corning ribbon alumina is 36–38 W/m-K, measured by a hot disc method.[6] Due to its ultrathin thickness, the thermal resistance of 40 μmt alumina ribbon outperforms alumina ceramic of standard thicknesses of 250 μm or more, and it is comparable to a 250 μmt AlN ceramic typically used in situations in which thermal conductivity is paramount, shown in Figure 4A and 4B.

Figure 4C illustrates the extreme thermal shock tolerance and rapid heat dissipation of 40 μm thick alumina ribbon ceramic. Alumina ribbon ceramic can withstand fast local heating over 1,400°C in the center, which would break most thick ceramics as thermal stress accumulates. After removal of the heating source, the body temperature quickly drops to room temperature within 15 second. This attribute could help solve heating problems as high speed, high function integration and device miniaturization becomes an increasing demand in advanced electronics.

OPTICAL PROPERTIES

Porosity scatters light very effectively, due to the large difference in refractive index between the gas-filled pores and the alumina matrix (n_{pore}~1, $n_{alumina}$~1.76). Figure 5 plots total and diffuse transmittance and scatter ratio from UV to near IR wavelength range on a 40 μmt alumina ribbon ceramic specimen for a sample–detector distance of 15 cm. The sample shows about 80% total transmittance in the visible range with a certain level of haze, which is visually illustrated by a set of comparison at zero distance vs. 15 mm between alumina ribbon ceramic and paper underlayment in Figure 5B. Transparency increases as the spectrum moves from visible toward the infrared region.

ELECTRICAL AND DIELECTRIC PROPERTIES

Alumina is one of the best-known low loss dielectric materials for high frequency signal transmission. In Figure 6A and 6B, the dielectric constant (D_k) and dielectric loss (D_f) of alumina ribbon ceramic were measured on an Fabry-Perot open cavity[7] from 10 GHz to 60 GHz and com-

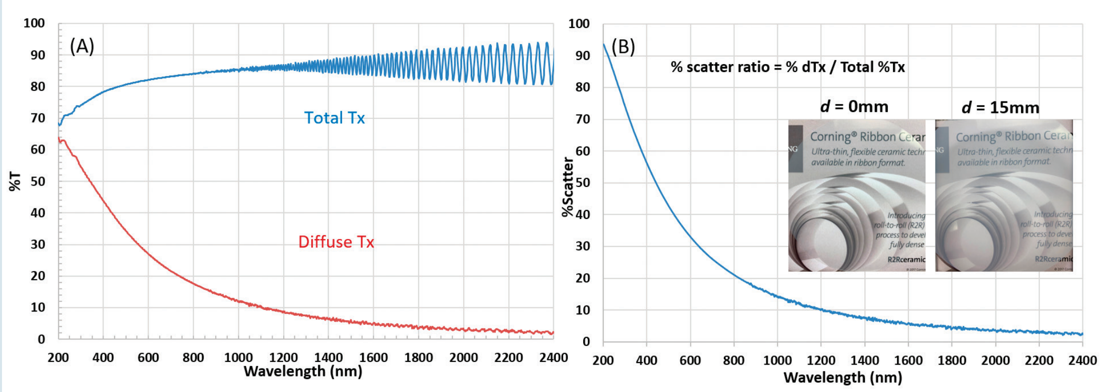

Figure 5. Transmittance and scattering curve of 40 µm thick alumina ribbon ceramic. Insert picture illustrates high translucency of alumina ribbon ceramics. *Credit: Corning, Inc.*

pared with commercial alumina ceramics (at different purity levels), fused silica, and one commercial low loss laminate. Because of its high purity and dense microstructure, alumina ribbon ceramics show remarkably low loss tangent ($D_f \sim 1 \times 10^{-4}$) across the entire test spectrum, which approaches the accuracy limit of this test method, indicating low dissipation of electromagnetic energy propagation. Coupled with high Dk of about 10, ultrathin alumina could enable device miniaturization and be attractive for a variety of RF devices, for example, compact passive devices, low loss and crosstalk waveguides, and small near-field antennae.

The loss tangent stays almost flat under a test frequency range up to 60 GHz and test temperatures up to 100°C (measured at 10 GHz on a split post resonator, Figure 6C). These properties enable device design across a wide bandwidth and application temperature range.

The DC breakdown voltage/dielectric strength of alumina ribbon ceramic was characterized and plotted in temperature and substrate thickness in Figure 6D (ASTM D149, DC voltage, oil for RT test, air for elevated temp). Alumina ribbon ceramic 40 µmt shows about 10 kV breakdown at room temperature and retains about 5 kV at elevated temperature of 300°C, with performance close to double for 80 µmt substrate at these temperatures (<300°C). These properties could be useful for miniaturization designs of power electronic devices.

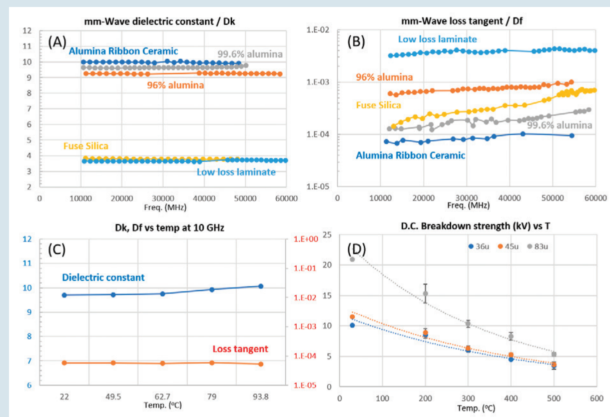

Figure 6. (A-B) Dielectric constant D_k and loss tangent D_f vs freq. on typical RF low loss materials, ceramics, fused silica and low loss laminate; (C) D_k/D_f vs Temp. at 10 GHz for alumina ribbon ceramic; (D) DC breakdown voltage (kV) vs temperature on various thicknesses of alumina ribbon ceramic. *Credit: Corning, Inc.*

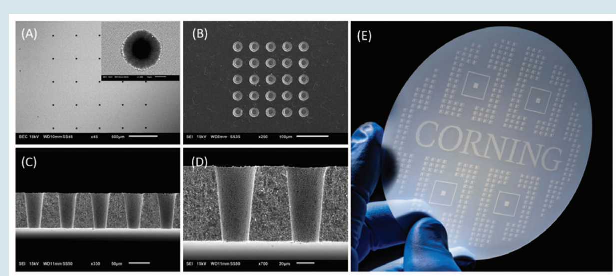

Figure 7. (A-B) 5x5 20 µm via array at different pitch (400µm, 40µm); (C-D) Various via cross sections; (E) Test pattern with about 25,000 40 µm size vias on a 40 µmt 4-inch alumina ribbon ceramic wafer. *Credit: Corning, Inc.*

MICROVIAS AND METALLIZATION

Microvias are holes up to 150 µm in diameter, generally laser-drilled, that connect layers in high density interconnect substrates and printed circuit boards. High quality microvia structures can be achieved directly on alumina ribbon ceramic through laser ablation, providing good thermal conductivity while maintaining thinness, which is essential for modern 3D electronics packaging design. Small via size and high via density are achievable on alumina ribbon ceramic at low aspect ratio (AR ~ 2 defined as substrate thickness/average via diameter) because of the material's thinness and good mechanical strength.

Figure 7A shows a 5 x 5 via array at 20 µm via diameter made in 40 µm thick alumina ribbon ceramic (at 400 µm center-to-center pitch), and Figure 7B (at 40 µm center-to-center pitch) corresponds to local via densities of 6 vias/mm^2 to 600 vias/mm^2. The via is taper shaped with a smooth inner wall, good edge quality, and no microcracks, as shown in Figure 7C and 7D.

Figure 7E is an example of a test via pattern constituting of about 25,000 vias at 40 µm via size and minimal 90 µm center-to-center pitch on a 40 µmt, 100 mm diameter alumina ribbon ceramic wafer.

Metal trace can be achieved by different means on alumina ribbon ceramic. Figure 8A shows a subtractive process for thin film metallization, including sputtered copper (or other metals) with a titanium adhesion layer, and a spin-coat photolithography process to define the pattern. Patterning with minimal 2 µm lines/spacings was demonstrated on 40 µmt alumina ribbon ceramic with a layer of 200 nm sputtered aluminum (SEM image of 5 µm line in Figure 8C). Although not shown here, we also achieved 1.5 µm L/S on 150 nm sputtered copper. Figure 8B shows a semi-additive process for thicker copper metallization, which uses a dry film photoresist for patterning, and the metal layer is built with electroplating process. Figure 8D shows minimal 10 µm lines/spacings achieved on 20 µm plated copper.

Microvias can be metallized either fully filled or conformal coated by choosing appropriate process parameters. Figure 8E gives CT scan images showing high quality via filling is feasible on both of 60 µm opening diameter filled via at 30 µm plated copper and 40 µm opening diameter conformally coated via with 10 µm plated copper. Figure 8F is a double side metallization test pattern with filled via by 20 µmt electroplated copper (minimal L/S: 10 µm); and Figure 8G is another example of aerosol jet printed pattern with 5 µm thick silver at 150 µm line width.

The ability of putting small and high density via and achieving fine line metallization is important to device design with high packaging density.

FLEXIBILITY AND ROLL TO ROLL PROCESSING

Thinness and flexibility enable flexible or conformal device design. Limiting bend radius is a function of thickness at a given modulus. Figure 9A plots bend stress vs. bend radius for different thickness alumina ribbon ceramic. A 17 mm bend radius on 40 µmt alumina ribbon ceramic yields 500 MPa bend stress on edge. Maximum bending should not exceed this number to avoid fracture, given its 600 MPa flexural edge strength. If using the 50% strength guideline, the recommended bending radius is 35 mm and 70 mm for 40 µmt and 80 µmt alumina ribbon ceramic, respectively, corresponding to 3-in and 6-in roller diameters. Figure 9B shows successful winding of a piece of 15 mm wide and 40 µm thick alumina ribbon ceramic strip on a 1.5-in diameter roller.

Thin flexible alumina ribbon ceramic provides a set of attractive attributes of high-performance technical ceramics; with its unique form factor, it can fit into many

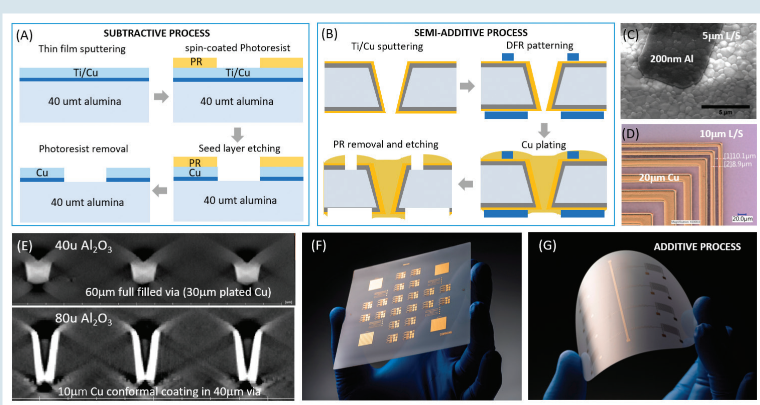

Figure 8. (A-B) Scheme of two photolithography processes for a patterned metallization layer on alumina ribbon ceramics; (C-D) Examples of pattern resolution with process A and B; (E) Via filling and conformal coating; (F) Example of direct plated copper (semi-additive process B); (G) Example of aerosol jet printing (additive process). *Credit: Corning, Inc.*

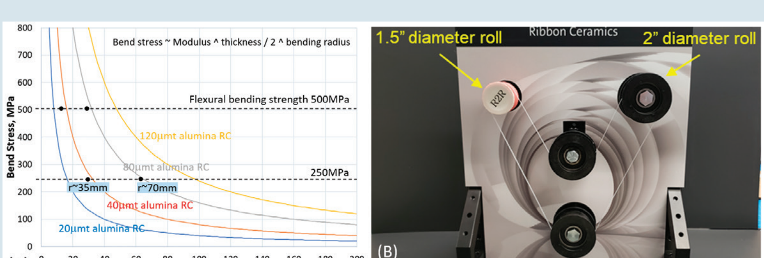

Figure 9. (A) Stress vs. bend radius over different thickness of alumina ribbon ceramic; (B) Example of conveying 40 µmt alumina ribbon ceramic. *Credit: Corning, Inc.*

unique designs in a broad application space. Potential application includes low loss substrate or waveguide for high speed data communication (from RF to THz), large size flexible sensors for high temperature or harsh environment, thermal management substrate for high power devices (LEDs, VCSELs), flexible heaters, and actuators, among others.

It has been demonstrated that alumina ribbon ceramic is compatible to those key downstream processes. However, as a thin inorganic material, handling could be challenging with current manufacturing processes that are designed around thick substrate. Further process developments, such as temporary bonding to a carrier and/or application to a continuous roll-to-roll process, could alleviate this challenge.

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