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Wafer-Scale Vitreous Carbon Molds Enabling Precision Glass Molding of Aspherical Lenses

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ABSTRACT

Glass optics tend to be advanced in comparison to polymer-based elements due to their higher refractive indices, better transmission in the UV and their thermal and chemical stability. As a result of this, glass components are commonly applied in demanding optical applications. Precision glass molding (PGM) is a standard process used to make aspheric glass lenses; however, conventional PGM uses precision-ground tungsten carbide molds with anti-adhesion coatings. This leads to high material and tooling costs, low scalability, and high energy use. Although wafer-scale precision glass molding (WSPGM) increases the throughput and energy efficiency, the broader implementation of this process is limited by two factors: the adhesion of the glass to the mold and the cost of fabricating multi-cavity molds.

In this work, we report a wafer scale vitreous carbon mold (WSVCM) developed via the carbonization of a replica of furan polymer as a superior and scalable alternative to WSPGM. Owing to the intrinsic low glass adhesion and high thermal stability of vitreous carbon, the WSVCM avoids anti-adhesion coatings, making the molding process easier; meanwhile, it also improves the durability during the use cycle of thermal repeatability. The mold is manufactured through replication-based route from diamond-turned master which allows high geometric accuracy along with much reduced tooling cost as compared with conventional precision grinding method. To guarantee dimensional fidelity, systematic precompensation of the master geometry is in place to compensate for carbonization induced shrinkage, there is also no issue in transferring aspherical profiles at wafer level. Furthermore, because of the integration of a concave spherical dots dicing architecture, thermomechanical stress concentration during cooling and demolding are mitigated, and reliable wafer level separation of the molded glass without fracture or residual adhesion is possible.

1 | Introduction

Aspherical lenses play a key role in modern optical systems where reduction of aberrations and increase of image reliability are still the highest goals [1–3]. Within this context, aspherical optics based on polymers are commonly produced using injection molding with additional diamond turned dies—lusted for its precision, economics, and ability to scale to complex geometries [4, 5]. However, polymers have a series of drawbacks, including poor

thermal and chemical resistances, mechanical robustness, ultraviolet transmittance, and durability, which make them highly unsuitable for high-performance optical applications. In contrast, glass devices offer significantly superior thermal stability, chemical resistance, mechanical stability and outstanding optical performance, being especially good in the ultraviolet and infrared spectral regions [6–8]. Unfortunately, conventional fabrication of glass aspheric shapes via grinding and polishing is time and cost intensive as well as being environmentally burdensome and

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not suitable for production of complex aspherical geometries in high throughput [9, 10]. These limitations have stimulated efforts to develop other fabrication techniques, which lead to scalable, reliable, and cost-effective fabrication of high-quality glass aspherical lenses.

Precision glass molding (PGM) is a well-established replication technology that is used to produce aspherical glass lenses with high reproducibility [11–15]. In a typical PGM cycle, the glass is heated into forming domain, pressed into a fitted precision mold, annealed to eliminate the remaining residual stress and cooled before demolding. While this process is well established for single component production, the use of conventional single cavity tooling limits the production throughput as well as the energy efficiency [16, 17]. Wafer-scale or multi-cavity molding concepts have, therefore, been pursued in order to increase the productivity and reduce the energy and cost per lens [12, 18, 19]. However, scaling to wafer-scale molds vastly increases the tooling complexity and cost (especially for ground tungsten carbide molds that must be specifically and precisely ground) as well as increases the process risk during the demolding process due to the increased contact area and integrated separation features that increase the chance of fracture, entrapment or sticking [20, 21]. Consequently, practical wafer-scale PGM requires mold materials and architectures that can form optical grade surfaces and dimensional fidelity while at the same time being able to remain manufacturable at a reasonable cost [22–24].

Carbon-based mold materials like glassy and vitreous carbon have gained attention as alternatives to conventional hard tooling as a result of their chemical inactivity and relatively weak wetting interaction with the molten glass, which make it possible to coat-free demolding [25–28]. Two main approaches to fabrication have been practiced. One is based on direct micro structuring of polished glassy carbon molds by combination of photolithography and ICP-RIE or similar subtractive processes to create multi-level diffractive or shallow refractive relief structures [28–30]. Although this approach provides both excellent surface finish and good control over the step heights to the micron scale, etch efficiency and profile fidelity become poor with increasing cavity depth and lateral area, and so this method is only suitable for planar or relatively shallow topographies instead of deep continuously varying refractive geometries like those used for aspherical microlenses. The second path uses replication of polymer precursor, and carbonization to create vitreous carbon molds and therefore, to transfer complex curved profiles without machining much [31–33]. While intrinsically more compatible to three-dimensional refractive geometries, previous demonstrations of this approach have been mostly limited to small-areas or isolated devices, in which case cavity-to-cavity uniformity, dimensional stability, and reliability during demolding are less of an issue than in integrated wafer-scale multi-cavity systems [34, 35]. Therefore, the effective application of carbon tooling techniques in optical imprinting technology and the achievable realization of wafer-scale refractive microlens array structures with deep geometries and large-area consistency is still not established enough.

To resolve this manufacturing issue, a wafer scale vitreous carbon mold (WSVCM) was achieved by a replication-carbonization

approach, which made it possible to build a 50 mm-diameter, 3 mm-thick mold with 45 aspherical cavities in one integrated substrate. The approach provides the ability to accurately transfer the deep three-dimensional refractive geometries from a precision master to a wafer-scale carbon under the mold, which can be used for precision glass molding applications. In addition to the demonstration of the dimensional integrity of the wafer scale the influence of integrated separation geometry on demolding reliability was systematically evaluated. Whereas fracture and trapping of glass was the standard condition upon judged square cross-section dicing architecture, a concave spherical dots configuration permitted steady release and unenviable wafer-scale reproduction under similar processing charges. The current study shows the development of a scalable vitreous-carbon mold that is conducive to wafer-scale precision glass molding (WSPGM) as well as the critical role of separation design in the reliable large-area demolding.

2 | Fabrication Process for WSVCM

WSVCMs with negative aspherical microlens array (MLA) cavities were produced by the carbonization of patterned furan polymer precursor. Although nanoimprinting lithography has become a promising fabrication strategy as proven in several studies lately [36], the current study uses a replication-based carbonization strategy due to its simplicity and scalability. The general fabrication process is shown in Figure 1a. The first one is to fabricate a nickel master mold with negative aspherical cavities with diamond-turning machining (DTM). An intermediate polydimethyl siloxane (PDMS) mold was then copied from the Nickel Master for additional casting of the polymer. A negative MLA geometry furan polymer precursor was cast and then cured thereafter in the PDMS mold. Finally controlled carbonization of furan precursor gave the WSVCM being decorated by well-defined aspherical MLA patterns.

2.1 | Fabrication of Nickel (Ni) Metal Master Mold

The fabrication of metal master wafer molds for aspheric lenses was achieved with diamond turning machining (DTM), a method which is known for machines of high robustness and precision. DTM allowed development of a nickel (Ni) master mold featuring 45 aspherical lens cavities in combination with a cross sectioned line dicing pattern in a square shape, as shown in Figure 1b. DTM provides unmatched flexibility and efficiency in manufacturing micro-optical components, especially structures that require high accuracy of field radius and high surface finish—requirements needed for the performance of aspherical lenses. While the ultimate durability of the master mold is not a severe requirement of WSVCM fabrication using micro-replication, the use of Ni master imparts considerable advantages. These include superior machinability, dimensional stability, and high replication fidelity. Consequently, this set of material properties ensures a good pattern transfer and consistency throughout the replication process and is better than the traditional physical and chemical fabrication methods.

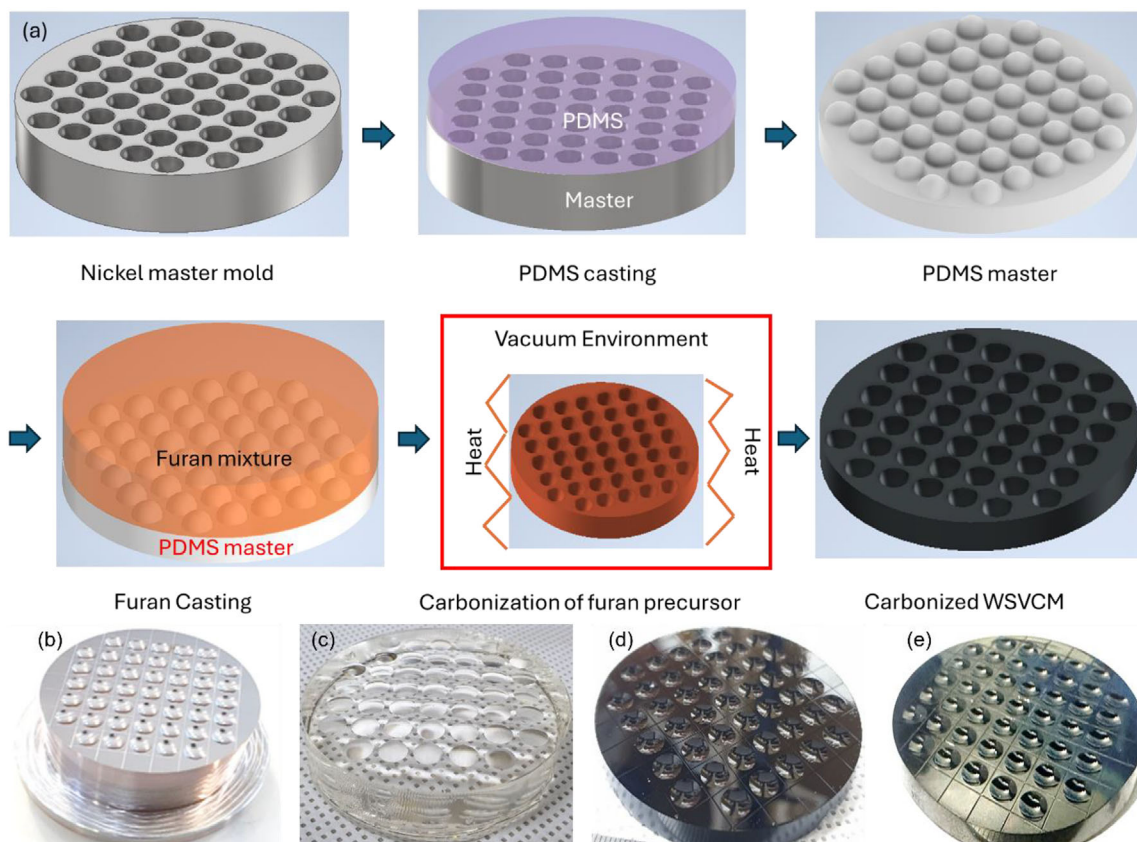


FIGURE 1 | (a) Schematics illustration of fabrication process of WSVCM, (b-e) Digital images of fabricated WSVCM with square line dicing keys (b) nickel master, (c) PDMS master, (d) polymer precursor, and (e) fabricated WSVCM.

2.2 | Fabrication of Intermediate PDMS Mold

To prevent adhering the furan resin to metallic substrates and protecting the nickel (Ni) master over several cycles of microreplication, we used intermediate molds made from polydimethylsiloxane (PDMS). As shown in Figure 1c, these PDMS molds have a positive aspherical lens pattern and contain some square dicing features, and these were derived from the Ni master mold. The fabrication process consisted of the blending of Sylgard 184 A along with Sylgard 184B, the curing agent associated with Sylgard at the recommended ratio according to the manufacturer. To remove the entrapped air, the mixture was degassed in a vacuum chamber before it was poured onto the Ni master. The resultant assembly was then cured under ambient conditions for a period of 24 h, which was used because it limited the shrinkage of the dimensions and to ensure dimension stability of the mold. Upon the processing of the cure period, the PDMS molds were carefully demolded from the master and used for further replication processes.

2.3 | Fabrication of Polymer Precursor

Furan resin was chosen as the precursor for fabrication of WSVCM precursor as shown in Figure 1d because of its high carbon yield, thermosetting properties and ease of processing. To reduce the level of inorganic contamination, the commercial resin was pretreated before use (details in Supporting Information; Figure S1), to reduce the level of impurities that may have

inherent in the surface quality after carbonization treatment. Polymerization was conducted under the acid-catalyzed conditions of nitric acid which acted as a curing agent. The precursor mixture was 94.8 wt.% furan resin, 5 wt.% ethanol and 0.2 wt.% nitric acid after vacuum degassing to eliminate the entrapped air. The homogenous solution was poured into a PDMS mold cast from a diamond turned nickel master and thermally cured according to a controlled course of heat (50°C–100°C at 0.5°C min⁻¹). Isothermal holds at 10°C steps (700 min each) were applied so as to achieve homogeneous crosslinking and stepwise evolution of volatile species so that the generation of internal stress and defects before carbonization is minimized.

2.4 | Carbonization of Polymer Precursors

Carbonization process for the cured furan precursor material was carried out under high vacuum (5×10^{-2} Pa) in order to have control over the removal of volatile species that are produced during pyrolysis. This polymer to carbon transformation process is accompanied by a process of dehydration, condensation, and structural rearrangement involving significant loss of mass and shrinkage in volume. If not carefully controlled the rapid gas evolution in this stage can lead to internal porosity and build up in stress and deformation of the aspherical cavities. In order to tackle these risks a multistage thermal profile has been used, and entire temperature and time history is presented in the Supporting Information (Figure S2). The process involved extended isothermal holds through critical decomposition regimes giving

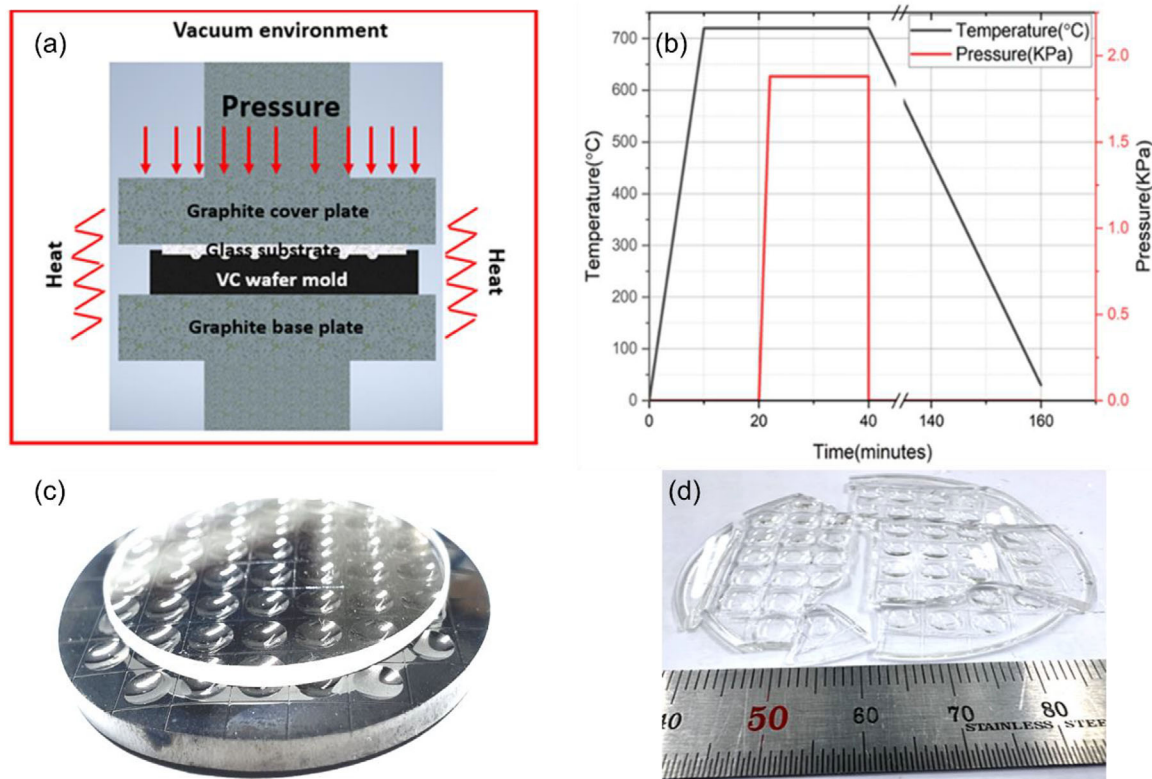


FIGURE 2 | Glass molding process for the fabrication glass wafer: (a) schematic diagram of glass molding machine, (b) temperature and pressure history of glass molding machine, (c) WSVCM with glass substrate, and (d) molded glass wafer.

an average heating rate of about $0.05^{\circ}\text{C}/\text{min}$ till it reached a final temperature of 1000°C . The slow heating schedule with a decreased pressure stimulated a slow evolution of the gas by products and minimized thermal gradients in 50 mm WSVCM as illustrated in Figure 1e. After reaching the temperature of 1000°C , the samples were allowed to cool down from the furnace naturally to room temperature to further remove residual thermal stress. Additionally, structural integrity of the carbonized molds was thus tested by optical microscopy of all the surface and cross-sectional areas (Figure S3). Crack/ delamination/ internal pore related defects were not observed in the aspherical cavities. The controlled vacuum environment and carefully staged thermal conversion provided for fabrication of defect-free WSVCM having preserved cavity geometry.

3 | Wafer Scale Glass Molding

Glass wafers were shaped by using the fabricated WSVCM with a square cross sectional dicing pattern in an infrared precision glass molding device, as shown in Figure 2a. The molding operation was performed at an optimized temperature of 720°C and a pressure of 541.8 kPa, the conditions presented in Figure 2b. Soda lime glass, which has good optical transmittance and glass transition temperature (T_g) of 546°C , was used as molding substrate. The molding cycle consisted of four consecutive steps such as (1) heating of glass substrate and WSVCM at a molding temperature, that is, at a rate of $70^{\circ}\text{C min}^{-1}$ (Figure 2c); (2) keeping the mold at the target temperature for 10 min to reach thermal

uniformity; (3) applying the pressure of mold making for 20 min; and (4) cooling at ambient temperature before demolding.

Process optimization was conducted by systematically adjusting the temperature and pressure conditions, so that high dimensional accuracy and good surface profile fidelity was obtained. However, despite these optimized parameters, the molded glass wafer broke during cooling as shown in Figure 2d. This failure was associated with stress concentrations that arise from the sharp edges of the square cross-sectioned dicing keys that led to crack initiation and propagation during thermal contraction. These results are important for underlining the crucial role of dicing key geometry on wafer-scale glass molding and the need for optimized dicing designs for mitigating stress-induced failure.

3.1 | Design Optimization of Dicing Key

To address the fracture and glass trapping of glass caused by conventional square cross-sectioned dicing keys (Figure 3a), the separation geometry of WSVCM was changed to a concave spherical-dot pattern (Figure 3b). The mechanical basis of this modification is based on the theory of classical stress concentration and fracture mechanics. Sharp corners are geometric discontinuities which have effectively zero radius of curvature. In the area of linear elasticity such corners are sources of stress singularities for which local stresses theoretically go to infinity as the radius of the corner approaches zero. Analytical and numerical analysis of the behavior of angular corners in

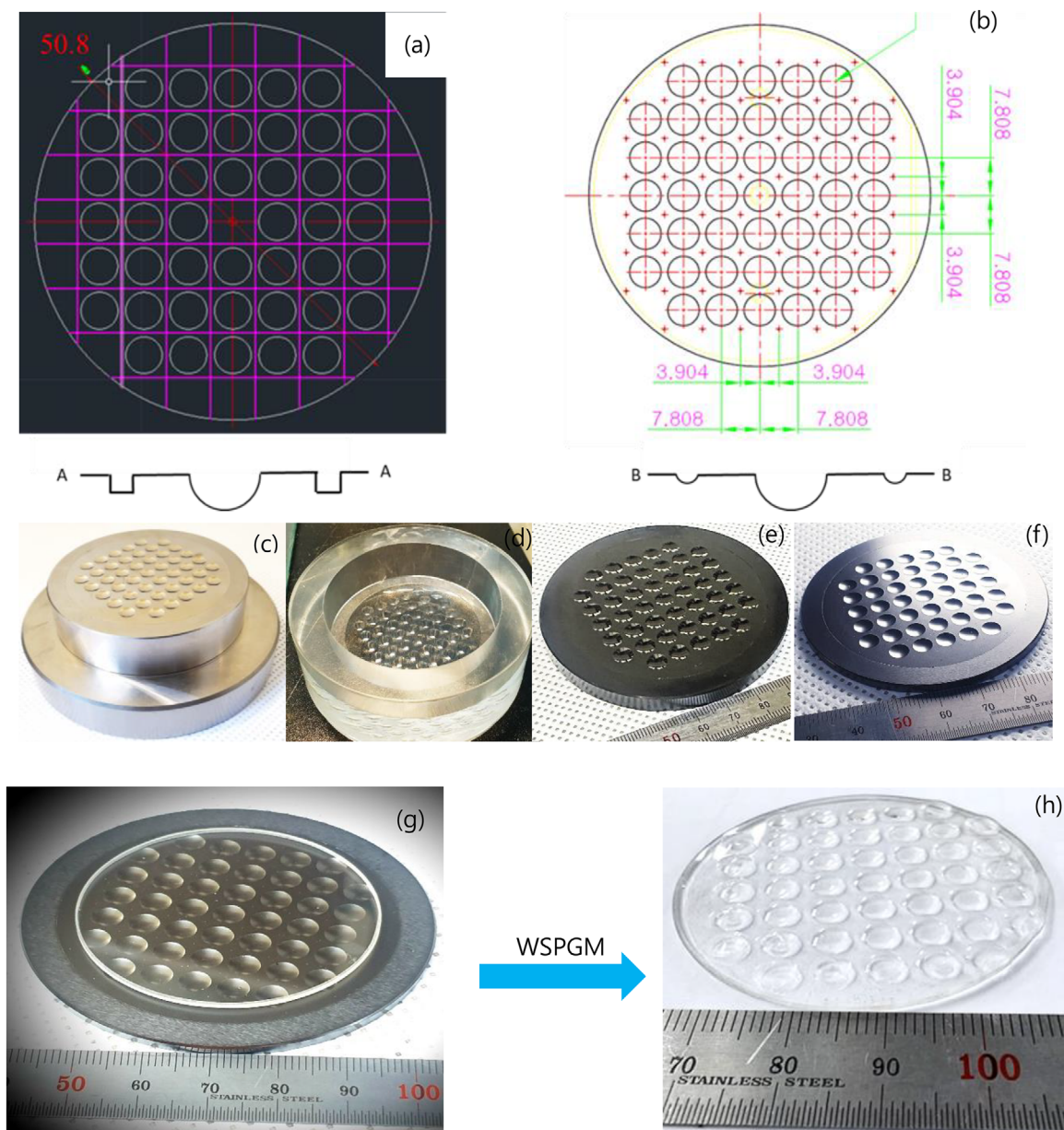


FIGURE 3 | (a) Design of WSVCM with square cross-sectioned dicing key; (b) Design of WSVCM with concave spherical dot dicing key; (c-f) digital progression of the fabrication process, from the nickel master mold to the final WSVCM, (c) nickel master mold, (d) PDMS mold, (e) Furan precursor, and (f) WSVCM with concave spherical dot dicing key; (g) WSVCM with glass substrate, (h) molded glass wafer (MGW).

plates has shown that stress intensity rises significantly as corner radius decreases and constraint increases, especially when the loading condition with tensile or thermomechanical loading is given [37]. During WSPGM, there is a differential thermal contraction between the glass and the vitreous carbon mold during cooling, as a result of mismatch between the coefficients of thermal expansion and elastic moduli, causing tensile stress in the glass close to constrained interfaces. In the case where separation features include sharp edges (as is the case in the square dicing architecture) these tensile stresses will be concentrated at the roots of the corner, wherein the local stress concentration factor (K_t) can be significantly increased. Increasing the local radius studies on rounded compared to sharp notch though confirm that brittle materials have lower stress intensity factors and crack initiation is delayed. Therefore,

under the condition of cooling-induced thermomechanical loading, square edge dicing keys serve as classical crack initiating sites [38].

The results of the experimental observations which are presented in the Supporting Information (Figure S4) are in full agreement with this mechanical interpretation. After using WSPGM with the square-key design, residual glass was evidently contained in the dicing areas. This trapped content creates a mechanical interlock that further brings local stresses to maximum during the demolding process in favor of crack initiation and propagation. In contrast to this no trapped glass was seen in the case of the concave spherical-dot design. The curved geometric eliminates the abrupt geometric discontinuities and adds a finite and varied radius of curvature. From a stress analysis point of view, such

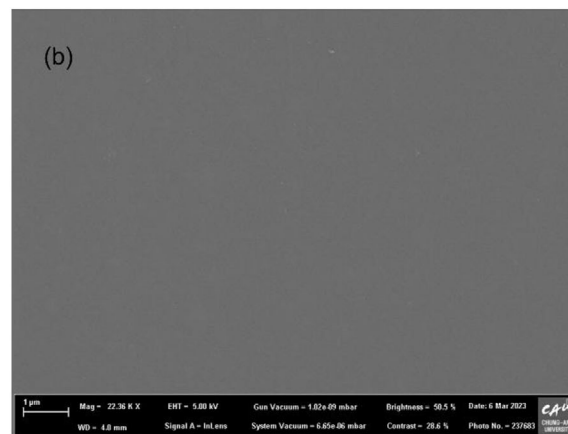
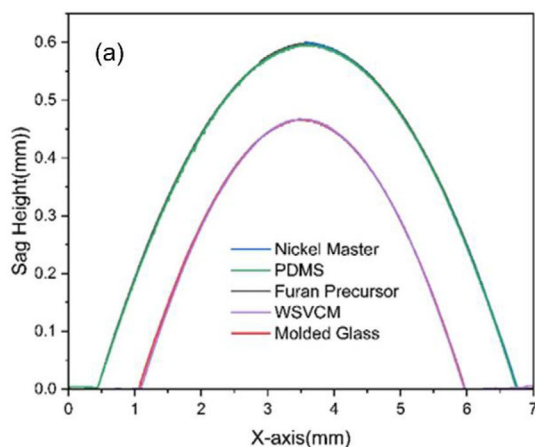


FIGURE 4 | (a) Comparison of cross-section profiles of nickel master mold, PDMS, furan precursor, WSVCM, and molded glass wafer; (b) SEM image of WSVCM.

curvature minimizes the peak tensile stresses and stress gradients at the interface such that crack nucleation is suppressed. In addition, considerations of contact mechanism are supportive of the improved behavior of the spherical geometry. During the cooling process separation of mold and glass does not take place instantaneously but in the course of time, with the reducing of the contact pressure. A smoothly curved dicing feature has the advantages of gradual loss of the area of contact, and progressive stress relaxation instead of the sudden relief of stress concentrated at a sharp edge. Thermomechanical modeling studies of the precision glass molding processes have shown that the main tensile residual stress is developed during the process of cooling and strongly affected with the geometric constraint conditions [39, 40]. Reducing the severity of geometric constraints is the reason that the spherical dot architecture reduces these tensile stress concentrations.

Under the same conditions in the molding process the revised WSVCM (Figure c–f) with the concave spherical dot dicing pattern has allowed a stable demolding and intact transfer of aspherical microlens array onto the glass wafer (Figure 3g,h), whereas the square design often leads to break or localized glass holding. These results show that separation-feature curvature has a decisive role to play in thermomechanical reliability of a wafer scale device. The improvement is therefore not just empirical but is commensurate with accepted principles for stress concentration lowering as well as brittle fracture reduction.

4 | Results and Discussion

4.1 | WSVCM

During the replication process, the PDMS intermediate mold and the cured furan precursor replicated from the nickel master mold with no recognizable change in the structure of the microlens geometry, which means the main change in dimensions was during the carbonization. The comparison of the cross-section profile in Figure 4a gives that the cross-section profile results from carbonization to get a systematic, anisotropic shrinkage of

WSVCM which is around 22% under the processing conditions used. Such shrinkage is inherent in polymer to carbon conversion and if not compensated, would result in the aspheric curvature changing and desirable deviations in the surface profile across the microlens array to occur. To eliminate this error, the precompensation of the master geometry was also doing at the diamond turning stage to increase the aspheric profile according to the shrinkage factors, made by the repeated fabrication trials, that the individual lens intends to be fabricated on, it was possible to determine the consistency of about 22% lateral contraction of the master to the WSVCM that allowed to predictively scale the geometry and uniformly control the dimensions of all lenses over the wafer. With this compensation, the WSVCM profile and the molded glass profile are coincident to $< 0.04 \mu\text{m}$ across the lens aperture very similar to the visual images which proves that the formation of the deformation by this carbonization effect was well enough recovered with master-level scaling. The shrinkage behavior and calibration framework has been described in detail in our previous work on vitreous-carbon microstructure [41] molds and technology was used here in the same manner to achieve high fidelity wafer-scale replication of aspherical micro-optical structures.

Furthermore, surface morphology and densification of the WSVCM were investigated using scanning electron microscope at 4 mm working distance as shown in Figure 4b, which reveals that the surface of WSVCM is dense and homogeneous with no visible open porosity and microstructural defects. Surface roughness was quantitatively characterized using confocal microscope and the quantitative arithmetical mean roughness was found to be $R_a \sim 2 \text{ nm}$ (Figure S5); it confirmed the formation of optically smooth surface after carbonization. Such nanoscale smoothness is needed for the precision glass molding process, because it will lower interfacial friction, suppress the occurrence of mechanical interlocking and lower the possibility of adhesion at high temperatures. In addition, although the phenomena of dehydration and volatiles evolution are irrational in polycondensation and carbonization of furan-based precursors, the scarce surface-connected pores observed in the obtained SEM micrographs and values for the nanometric roughness suggest the effectiveness of the densification under the adopted conditions

of curing and pyrolysis. The inherently low porosity, and smooth surface do not need anti-adhesive coatings as is the case in conventional mold systems where coating degradation and non-uniformity has a potential to result in a lack of dimensional stability and reliability in terms of maintenance. Collectively, these characteristics prove that the structural integrity and surface qualities of WSVCs are in line with the requirements of high-fidelity wafer scale transfer of aspherical micro-optical geometries.

4.2 | Geometrical Properties and Uniformity Analysis

To systematically assess the geometric integrity, dimensional accuracy, and reliability of replication of the WSVCs and the glass wafer aspherical MLAs, high resolution confocal microscopy was used throughout the entire fabrication and molding sequence. Four independently fabricated WSVCs integrated with concave spherical dot dicing patterns were used to fabricate four glass wafers by WSPGM under optimized processing conditions as shown in Figure 5a,b. To ensure a statistically robust and spatially representative evaluation of wafer-scale uniformity, a series of four aspherical lenses, distributed over different regions of each WSVC and corresponding molded glass wafer, were identified for a detailed evaluation. These lenses were sequentially labeled from WSVC11 to WSVC44 and molded glass wafer lenses MGW11 to MGW44 to enable a straightforward result of a one-to-one comparison of the features of the mold and the replicated glass formed at the same position in space (Figure 5d,e). High resolution confocal measurements were used to extract cross section surface profiles from the selected aspherical lenses from which form errors were calculated to quantitatively determine the replication accuracy and dimensional stability. A total of sixteen lenses analysis was carried out for WSVCs and additional sixteen for the molded glass wafers to provide a statistically meaningful validation of both mold fabrication precision and the glass replication fidelity (Figure 5c,f).

To further support wafer-scale uniformity, replication fidelity and repeatability of the processes, the single-lens surface profiles from four independent wafer-scale vitreous carbon molds, WSVC1, WSVC2, WSVC3 and WSVC4 were directly compared, as shown in Figure 5g. The close superposition between these profiles is a testimony of the very good reproducibility obtained in the fabrication of WSVC in independent replication cycles. Subsequently, these WSVCs were used to create four glass wafers using the WSPGM under the identical optimized conditions. The uniformity of the resulting molded glass wafers was stringently analyzed to identify uniformity over several replications. Four representative glass wafers, that is, MGW1, MGW2, MGW3, and MGW4 were selected for the characterization of their surface profiles in detail as shown in Figure 5h. Confocal measurements showed all of the WSVCs has form errors less than 3 μm whereas, the MGW lenses has form errors 5 μm , which are summarized in Figure . The detailed analysis showed very low geometric deviation between different lenses within the same wafer as well as between different wafers, indicating very uniform pattern transfer and wafer-scale dimensions and very good dimensional reproducibility. Consequently, the pro-

posed WSVC-based WSPGM process was confirmed as effective achieved consistent and high precision replication of aspherical microlens arrays over large areas, which is critical for reliable wafer scale optical manufacturing.

To further validate the accurate transfer and long-term preservation of the geometries of the lenses from the master mold to the final glass wafer, three-dimensional (3D) surface profiles of individual aspherical lenses were systematically measured across all of the fabricated WSVCs and the corresponding molded glass wafers, as shown in Figure 5j-m. The reconstructed 3D profiles show excellent match in overall lens morphology, sag height, and curvature distribution, which verifies that the designed aspherical geometry and granted critical dimension features have been always replicated throughout the full history of fabrication, including replication, carbonization, and wafer-scale precision glass molding.

This last complete 3D characterization gives direct spatial validation of the fidelity of the replicas and complements the 2D cross-section profile form error analysis. The close correspondence between the WSVC and glass lens surfaces shows that the WSPGM process using the WSVC can successfully preserve the global shape and the localized surface features in the wafer-scale. Importantly, no measurable deformation and distortion of geometrical integrity has been observed even when comparison is made between lenses made with lenses produced independently and replicated in several glass wafers. This consistency tells us that successful accommodation of the thermomechanical stresses imposed during the molding process and specified during cooling and demolding operations were accomplished without any compromise of the lens geometry. Such high 3D geometric reliability is especially important for advanced optical applications where even small deviations in the curvature or sag of the surface may result in high levels of aberrations, poor focusing efficiency, and reduced system level optical performance. Collectively, these results deliver the robustness, repeatability, and scalability of the proposed WSVC based WSPGM approach thus demonstrating its strong potential for the wafer-scale manufacturing of uniformly before glass aspherical optics.

5 | Conclusion

This study highlights the efficiency of WSVCs as a robust and scalable glass molding platform for high accuracy glass molding of aspherical microlens microarrays. Through a set of systematic experimental analysis techniques involving confocal microscopy, three-dimensional surface profiling, and cross-sectional characterization, we have verified that the present replication-based fabrication process allows to accurately transfer three dimensional-complex surface geometries of the master mold to the final glass wafers, which gave excellent dimensional-accuracy and uniformity. The geometry uniformities coming from individual lens to lens within a wafer and from wafer to wafer underline the reliability and repeatability of the WSVC-based molding WSPGM. A critical outcome of this work is the identification of mold dicing design as an important determinant of mold molding wafer success. While the traditional square cross section line dicing is prone to stress concentration, resulting in

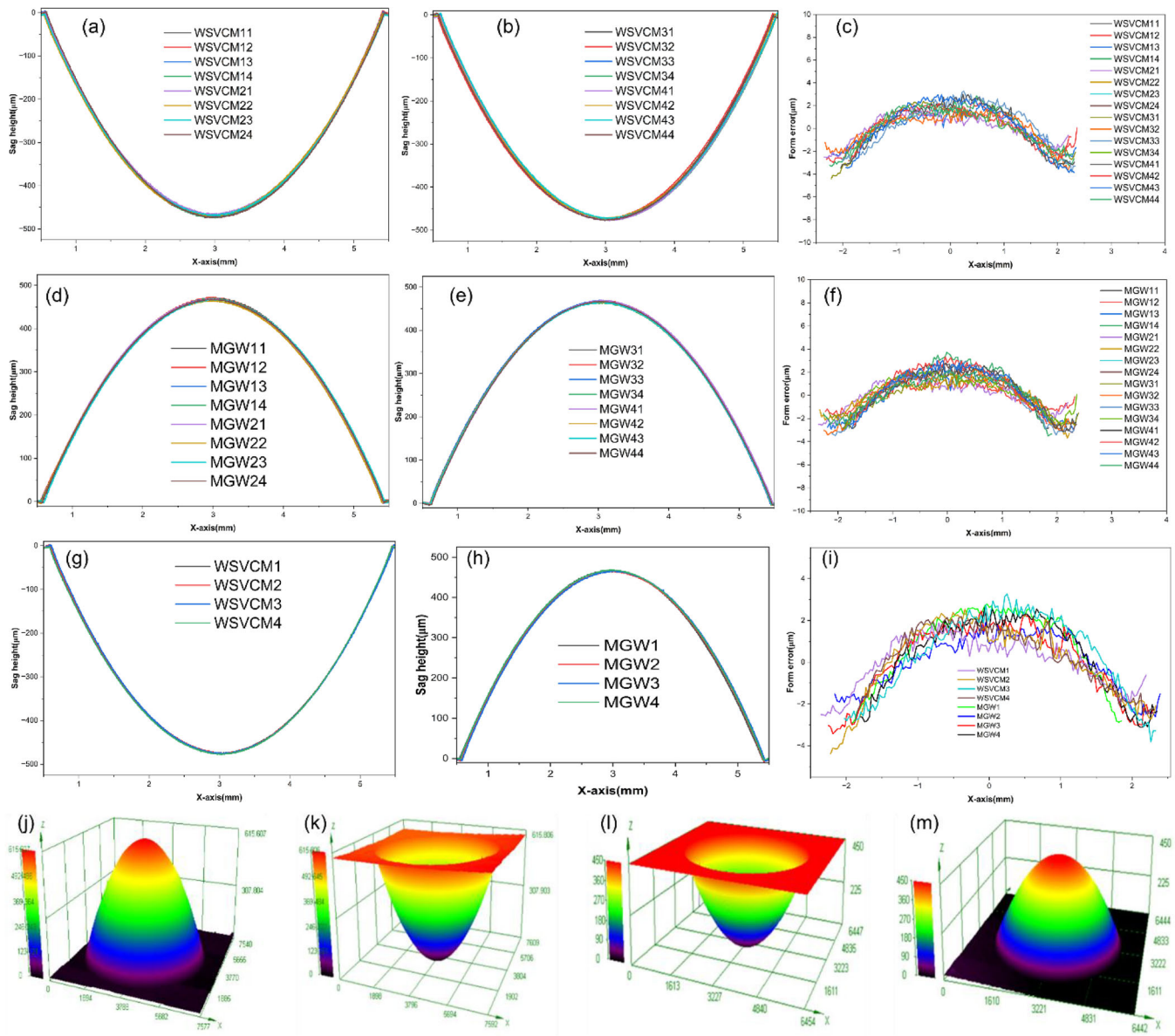


FIGURE 5 | (a) Comparison of cross-sectional lens profiles of WSVCM1 and WSVCM2 measured at four different locations within a single WSVCM, (b) comparison cross-sectional lens profiles of WSVCM3 and WSVCM4 measured at four different locations within a single WSVCM, (c) form error analysis of the sixteen selected aspherical lenses on the WSVCMs, (d) comparison cross-sectional lens profiles of MGW1 and MGW2 measured at four different locations within a single MGW, (e) comparison cross-sectional lens profiles of MGW3 and MGW4 measured at four different locations within a single MGW, (f) form error analysis of the sixteen selected aspherical microlenses on the molded glass wafer(MGW), (g) comparison of single-lens cross-sectional surface profiles extracted from four independently fabricated wafer-scale vitreous carbon molds (WSVCM1–WSVCM4), (h) comparison of single-lens cross-sectional surface profiles extracted from four independently molded glass wafers (MGW1–MGW2), (i) form error analysis of representative aspherical microlenses across the four molded glass wafers, (j) 3D surface profile of single lens of PDMS mold, (k) 3D surface profile of single lens of furan precursor, (l) 3D surface profile of single lens of WSVCM, (m) 3D surface profile of single lens of MGW.

the fracture of glass and mold failure, the concave spherical dot dicing design is good to deal with thermomechanical stress and easier to accomplish natural demolding during mold cooling. This optimized dicing geometry allows the fabrication of large area (50 mm) glass wafer without breakage or residual adhesion of glass, thus underlining the importance of this geometry for wafer scale glass optics. Furthermore, three dimensional and cross sections analyses support accurate replication of the structure of the microlens array profile with the sag depth of the molded glass lenses like that of the WSVCMs, which serves as a conformity

check. The reproducibility obtained using several molds and glass wafers provides the robustness of the proposed process under the same molding conditions.

Beyond the accuracy of replication, the WSVCM-based approach that is proposed also has significant benefits in terms of cost efficiency and scalability. The diamond turned master molds approach coupled with a replication and carbonization approach enables multiple WSVCMs to be produced economically and avoids the need for anti-adhesion coatings. By including shrink-

age compensation when the master design is made, a fine degree of dimensional control of the final glass optics is attained. Collectively, these results make WSVC enabled wafer scale precision glass molding a promising manufacturing strategy for high throughput production of high-performance glass aspherical optics to address key limitations of conventional precision glass molding technologies.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

Supporting File: jace70726-sup-0001-SuppMat.docx.