Full length article

Athermal glass work at the nanoscale: Engineered electron-beam-induced viscoplasticity for mechanical shaping of brittle amorphous silica

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Abstract

Amorphous silica deforms viscoplastically at elevated temperatures, which is common for brittle glasses. The key mechanism of viscoplastic deformation involves interatomic bond switching, which is thermally activated. Here, we precisely control the mechanical shaping of brittle amorphous silica at the nanoscale via engineered electron–matter interactions without heating. We observe a ductile plastic deformation of amorphous silica under a focused scanning electron beam with low acceleration voltages (few to tens of kilovolts) during in-situ compression studies, with unique dependence on the acceleration voltage and beam current. By simulating the electron–matter interaction, we show that the deformation of amorphous silica depends strongly on the volume where inelastic scattering occurs. The electron–matter interaction via e-beam irradiation alters the Si-O interatomic bonds, enabling the high-temperature deformation behavior of amorphous silica to occur athermally. Finally, by systematically controlling the electron–matter interaction volume, it is possible to mechanically shape the brittle amorphous silica on a small scale at room temperature to a level comparable to glass shaping at high temperatures. The findings can be extended to develop new fabrication processes for nano- and microscale brittle glasses.

1. Introduction

Glass, a very hard and chemically stable material, has, since ancient times, seen increasingly ubiquitous use because of its formability. Under high temperatures, glass is easily transformed into useful shapes using a wide range of glass crafting techniques. Its mechanically formable nature is due to viscoplastic deformation of the amorphous material at high temperatures (exceeding the glass transition temperature, Tg). Amorphous silica mainly consists of strong covalently bonded silicon and oxygen atoms which are abundant elements in the Earth’s crust. The strong covalent bonds are switchable at temperatures exceeding Tg; only under these conditions does amorphous silica deformat viscoplastically to enable forming. Although small-scale amorphous silica has become integral to advanced electronics [1–7], biomaterials [8–12], and 3D nanostructured materials [13–15], its temperature-dependent formability limits process compatibility. Recently, significant improvements in formability of amorphous silica have been reported under electron beam (e-beam) irradiation [16–22]. Zheng et al. reported that the e-beam of conventional transmission electron microscopy (TEM) induces the ductile plastic deformation of amorphous silica [16]. They explained that the electrons accelerated at 300 kV introduce vacancies in the amorphous silica by elastic collision, leading to the ductile plastic deformation. However, a systematic study on the underlying deformation mechanism is still lacking.

In this study, we elucidated the room-temperature viscoplastic deformation behavior of amorphous silica on a small scale (from nano- to micrometer) based on the inelastic scattering interaction between electrons and matter using a focused e-beam with low acceleration voltage in scanning electron microscopy (SEM). Particularly, we showed that irradiation effect by e-beam irradiation is the key mechanism behind viscoplastic deformation behavior of brittle amorphous silica, neither knock-on damage nor temperature increase. To enhance our understanding and inform practical applications, the irradiation effects of a wide range of e-beam...
conditions on amorphous silica were studied; in particular, the e-beams with low acceleration voltages from a few to tens of kV were used to avoid e-beam damage. We systematically performed in-situ SEM compression tests while modulating parameters such as the acceleration voltage, current density, and spatial area of irradiation. Other studies used fixed high-acceleration-voltage (hundreds of kV) e-beams characteristic of CTEM [16–22]. Consequently, we were able to analyze e-beam-induced plastic behavior in terms of the interaction between the incident electrons and matter in conjunction with Monte Carlo simulations. The ductile plastic deformation behavior of amorphous silica under e-beam irradiation is directly related to the electron–matter interaction volume. Our experiments and simulations showed that transmitted and scattered electrons can alter the bond nature of amorphous silica, and it was confirmed that a negligible temperature increase occurred under e-beam irradiation. Finally, based on this understanding, we demonstrate the feasibility of small-scale mechanical shaping of amorphous silica under scanning e-beam irradiation. Systematically controlling the electron–matter interaction volume enables a mechanical shaping of brittle amorphous silica on a small scale at room temperature to a level comparable to glass shaping at high temperatures.

2. Experimental methods

2.1. Sample preparation

To investigate the e-beam-induced deformation behavior, we fabricated various amorphous silica nano/microstructures: nanospheres, nanoshell spheres, and micropillars. The amorphous silica nanospheres were fabricated using the sol–gel Stöber process. Through hydrolysis and polycondensation, submicron-sized solid silica spheres were synthesized in solution from the molecular precursor tetraethyl orthosilicate (TEOS). Subsequently, the amorphous silica nanospheres were transferred onto a sapphire substrate through spin coating [23]. As-fabricated amorphous silica spheres contain residues such as physically absorbed water, residual solvent, and pyrolyzed CH₂. To remove the residues and fix the spheres onto a sapphire substrate, heat treatment was conducted at 900°C for 6 h in an argon atmosphere [24,25]. Fig. S1 (a) shows thermogravimetric analysis (TGA) curves of the as-fabricated silica nanospheres during the first and second heat treatment. This suggests that most of the residues were removed during the first heat treatment. Through X-ray diffraction (XRD) analysis and cross-sectional TEM analysis (Fig. S1 (b, c)), we confirmed that the amorphous silica nanospheres maintained their amorphous phase after heat treatment. Fig. S1 (d) shows that the nanospheres on the sapphire substrate after fabrication and heat treatment had a uniform spherical geometry with a narrow diameter distribution (average diameter of 290 nm, Fig. S1 (e)). Moreover, they were free of irradiation damage, unlike silica spheres synthesized by an ion-beam milling process. The micropillars were fabricated on a fused quartz (amorphous silica) substrate using focused ion-beam (FIB) milling. An ion-beam with 30 kV acceleration voltage was used for both coarse milling (3 nA) and fine milling (10 pA) of the substrate. The diameter, height, and taper angle of the pillars were 280 nm, 900 nm, and 2.6°, respectively.

The amorphous silica nanoshell spheres with a shell thickness of 20 nm were fabricated by synthesizing an amorphous silica thin film on polystyrene (PS) spheres. PS spheres with a diameter of 250 nm were subjected to the Stöber process to fabricate PS–amorphous-silica core–shell spheres. The core–shell spheres were deposited onto a sapphire substrate by spin coating. Finally, the PS-sphere were removed by vaporization during the heat treatment at 900°C for 6 h under an argon atmosphere, and hollow spherical amorphous silica nanoshells were obtained.

2.2. In-situ SEM mechanical tests

To investigate the e-beam-induced deformation, we conducted compression tests on the amorphous silica nanospheres, micropillars, and spherical nanoshells using an in-situ nano-indentation system (Hysitron PI-85 SEM PicoIndenter®) mounted onto an SEM stage (FEI Quanta FEG-250 and FEI Nova 600 NanoLab). The thermal drift was compensated by measuring the drift rate for 40 s before each compression test. For the amorphous silica nanospheres and spherical nanoshells, in-situ compression tests were performed at a constant loading rate of 0.4 μN/s. For these spherical specimens, we used a cono-spherical indenter with a curvature diameter of 1 μm (Fig. S2) to ensure that the e-beam irradiation pathway was not partially blocked by the indenter tip (as would occur when using a flat punch indenter). For the micropillars, we conducted a strain-rate sensitivity analysis by performing in-situ compression tests under e-beams with various acceleration voltage (Vₐ) and current density (J) conditions (beam off: 2 kV and 1.6 A/m²; 5 kV and 1.4 A/m²; 18 kV and 2.0 A/m²; and 30 kV and 2.4 A/m²) at strain rates from 0.0006 to 0.014/s using a 500-nm-radius flat punch indenter. Moreover, for mechanical shaping of the fused-quartz micropillars, the e-beam was irradiated on a limited area (width of 250 nm and height of 100 nm) of the side surface of the pillar. The experimental parameters for e-beam irradiation are listed in Table S1.

2.3. Monte Carlo simulation of electron–matter interaction

To describe the electron–matter interaction, we constructed a model reflecting the geometry of an amorphous silica nanosphere using Monte Carlo simulation software (CASINO® software (Ver. 3.3)) into which the experimental e-beam conditions were input. To construct the model, we excluded the sapphire substrate and only considered the amorphous silica. This is because there is no noticeable ductile plastic deformation or softening of sapphire under e-beam irradiation (Fig. S3). We additionally investigated the deformation behavior of a sapphire micropillar fabricated by FIB milling under e-beam irradiation (10 kV and 27.9 A/m²) and confirmed that the stress–strain curves with and without e-beam irradiation are almost identical. Therefore, we constructed the electron-matter interaction model based on the amorphous silica sphere and the e-beam scanning profile. In the model, assumptions were necessary regarding the e-beam to account for the timescales involved in the electron–matter interactions and SEM e-beam irradiation. The lifetime of an electron excited by the interaction is <1 ps. However, once the electron absorbs sufficient energy to escape a solid, it leaves behind a localized charge within the material [26]. The settling time (τ) of this charge depends highly on the resistivity of the material:

\[
\tau = \frac{\varepsilon_0 \varepsilon_R \rho_R}{c_1 (c_2 \rho_R + c_3 \rho_R^2 + c_4 \rho_R^3 + \rho_R^4 + \rho_R^5 + \rho_R^6 + \rho_R^7)}
\]

where \(\varepsilon_R\) and \(\rho_R\) are the relative permittivity and the resistivity of material, respectively. For submicron-thickness insulators, such as the amorphous silica nanospheres in this study, τ reaches approximately several hundred microseconds [27–30]. The SEM e-beam used in this study completes one horizontal scan of the sphere in 100 μs (Fig. S4). This is insufficient to allow charge relaxation, even for the charges generated at the beginning of the scan. However, for the irradiation profile used in this study, there was an interval of ~400 μs between each horizontal scan of the sphere, as the SEM e-beam scanned both the nanosphere and sapphire substrates. This interval is sufficiently long for the charges in the amorphous silica nanosphere to relax. Therefore, we assume that the
e-beam-induced deformation of the amorphous silica nanosphere is due to the electron–matter interaction during a single horizontal scan. Hence, we constructed an interaction model of an amorphous silica nanosphere under a single horizontal scan by the e-beam. The density and work function of the amorphous silica were set at 2.2 g/cm³ and 9.9 eV, respectively. The same conditions were applied for models of an amorphous silica micropillar and spherical nanoshell because they also had diameters of 280 nm. The numbers of electrons corresponding to the experimental e-beam parameters are listed in Table S2.

2.4. Finite element simulation for analysis of electron-beam-induced temperature change

We conducted finite-element (FE) analysis of the temperature change of the nanostructures under e-beam irradiation using general FE analysis software (ABAQUS/Standard (Ver. 6.10)). We calculated the temperature change in a micropillar under 5 kV, 1.4 A/m² e-beam. To simplify the calculation, we treated the e-beam as stationary, unlike the raster SEM e-beam. We developed a heat-transfer model of the micropillar and substrate and applied 4-node axisymmetric diffusive heat-transfer elements with adaptive meshing (Fig. S5). At the top surface of the pillar, a cylinder-shaped volume, with a radius and height of 4 and 33 nm, respectively, is where the body heat flux is imposed. To set the body heat flux, we referred to the Monte Carlo simulation results. The Monte Carlo results showed that when a stationary e-beam irradiates the center of the side surface of the micropillar, a cylindrical volume with a radius of 4 nm and height of 33 nm absorbs most of the energy (with the same number of electrons as a 5 kV, 1.4 A/m² e-beam; Fig. S5 (a)). We assumed that the absorbed energy was completely converted into thermal energy and the corresponding body heat flux was imposed for 120 μs (Fig. S5 (b)). The heat-transfer type was considered transient conduction with no convection. The density, thermal conductivity, and specific heat capacity were set at 2.2 g/cm³, 1.46 W/(m·K), and 700 J/(kg·K), respectively. The temperature at the bottom of the substrate was fixed at 298 K. The temperature change is thought to be overestimated, as the model does not consider the characteristic raster scanning mode of the SEM e-beam and the thermal contact between the micropillar and flat-punch diamond indenter, which has a high thermal conductivity of 3320 W/(m·K).

2.5. FE simulation of electron-beam-induced mechanical shaping

We conducted FE analysis on the mechanical shaping under e-beam irradiation using the same ABAQUS package. This is possible by treating the amorphous silica subjected to scanning e-beam irradiation as a composite of e-beam interaction and non-interaction volumes. First, we determined the mechanical properties of the amorphous silica during interaction with incident electrons and in the absence of incident electrons. Using the compression load–depth curves under no irradiation and 5 kV, 279 A/m² e-beam irradiation, we determined the plastic flow curves of the non-interaction and interaction volumes, respectively. Under 5 kV and 7.9 A/m² e-beam condition, the entire volume interacts with the incident electrons. Fig. S6 shows an FE model simulating the compression test of an amorphous silica nanosphere. To simplify the calculations, we assumed that the deformation of an amorphous silica nanosphere was elastic–plastic, not elastic–viscoelastic. The indenter and sapphire substrate were assumed to be spherical rigid and elastic bodies, respectively. A 4-node axisymmetric solid element with reduced integration (CAX4R) was used for meshing the sphere and substrate. The substrate with a height and width of 3 μm had a mechanical boundary condition wherein the bottom face was constrained to prevent rigid body motion and rotation. A vertical load in the y-direction was applied to the indenter with a loading rate of 0.4 µN/s until the maximum load of 100 µN was reached. The interactions between each material were controlled using a mechanical surface–to-surface contact pair algorithm, wherein the normal behavior was specified as a hard contact and the tangential behavior was assumed to be frictionless. The elastic modulus, Poisson’s ratio, and density of the sapphire substrate were set as 425 GPa, 0.3, and 3.98 g/cm³, respectively, while those of the amorphous silica nanosphere were set as 70 GPa, 0.17, and 3.51 g/cm³, respectively. The plastic behavior was initially defined based on the literature [16], and then later optimized. To establish the plastic flow curves of the amorphous silica interacting or not interacting with the e-beam, we used a least-squares approach that minimizes the differences between the load–depth curves obtained using experimental and computational compression tests of the amorphous silica nanospheres. The objective function (f) is based on the nonlinear least-squares method and is defined as follows:

\[
f = \min \sum_{i=1}^{N} \left( \hat{F}_i^{exp} - \hat{F}_i^{cal} \right)^2 \tag{2}
\]

where \( \hat{F}_i^{exp} \) and \( \hat{F}_i^{cal} \) are the respective experimental and calculated load (F) values at the \( i \)th depth normalized using the measured maximum load. The number of extracted data, \( N \), was set as 10. We incorporated these plastic deformation characteristics in the FE model with e-beam interaction and non-interaction volumes that were estimated from the Monte Carlo simulation for each beam condition.

Fig. S7 shows the FE model used to simulate the compression test of a micropillar with a diameter, height, and taper angle of the pillar were 280 nm, 900 nm, and 2.4°, respectively. The pillar had the same mechanical properties as the amorphous silica nanosphere, and the flat punch indenter was assumed to be a rigid body. The mesh type (CAX4R), contact condition between the indenter and pillar, and the boundary condition applied to the bottom face of the micropillar are the same as in Fig. S6. A vertical displacement in the y-direction was applied to the indenter with a strain rate of 0.006/s until the maximum depth of 136 nm was reached. Fig. S8 shows the FE model used to simulate the compression test of the spherical amorphous silica nanoshells. The model structure was the same as in Fig. S6 and only the compressed material was changed from a sphere to a spherical nanoshell.

3. Results and discussion

3.1. Unique plastic deformation behaviors of amorphous silica nanospheres under spatially focused scanning e-beam irradiation with a low acceleration voltage

Scanning e-beams with low acceleration voltages clearly induce the immediate plastic deformation of the amorphous silica nanospheres under compression despite the completely different e-beam irradiation conditions compared to those used in previous CTEM studies. Fig. 1 shows the differences in the deformation behavior with and without e-beam irradiation (10 kV, 27.9 A/m² e-beam). In the absence of e-beam irradiation, most deformation is elastic and minimal plastic deformation occurs. Fig. 1a–1 shows the load–depth curve (black) of the compression test under an applied load of 100 µN without irradiation. The maximum compression depth is 43 nm, but the residual compression depth is only 10 nm due to the subsequent elastic recovery. There was little difference in the shape of the amorphous silica nanosphere before (Fig. 1a–2) and after compression (Fig. 1a–3). The limited plastic deformation under compression may be due to a densification of the amorphous silica [31–33]. The compression tests un-
under larger applied loads (e.g., 200 μN) induced brittle fracture of the amorphous silica, which is indicated by pop-in events in the compression load–depth curve (Fig. S9) and a meridian crack on the surface of the nanosphere (Fig. 1(a-4)). However, under scanning e-beam irradiation, the amorphous silica nanosphere becomes ductile, undergoing significant permanent plastic deformation. The compression load–depth curve under an applied load of 100 μN and e-beam irradiation (blue curve, Fig. 1(a-1)) is less steep than that without irradiation (black curve, Fig. 1(a-1)). The maximum compression depth reaches 149 nm, and the residual compression depth after unloading is 140 nm, indicating that the deformation was mostly plastic. A series of snapshots (Fig. 1(a-5)) and Movie S1 consistently show that the amorphous silica nanosphere continuously deformed along the indenter and was flattened into a disk (Fig. 1(a-6)) by the compression. There was no cracking on the nanosphere surface, even after significant plastic deformation. Moreover, the result of mixed-mode compression test (i.e., performed while alternating between beam-off and beam-on conditions) suggests that the nanosphere immediately transitions between ductile and stiff responses depending on the presence of e-beam irradiation. As shown by the compression load–depth curve in Fig. 1(b) and the corresponding in-situ Movie S2, the slope decreased by a factor of four upon e-beam irradiation. Conversely, without e-beam irradiation, the slope was similar to the original slope, i.e., the brittle nanosphere became ductile immediately upon e-beam irradiation. Similar e-beam-induced ductile plastic
deformation of amorphous silica was reported when an entire nanosphere was irradiated using a CTEM e-beam with an acceleration voltage of 200–300 keV [22]. Notably, our research conducted using SEM demonstrates that the same ductile plastic deformation is observed even when a spatially focused e-beam with an acceleration voltage 30-times lower than that of the CTEM e-beam scans the amorphous silica nanosphere following a raster pattern.

Subsequent tests demonstrated that the plastic deformations of the amorphous silica spheres depend uniquely on $V_A$ and $J$ of the e-beam. We systematically conducted compression tests on the amorphous silica nanospheres under applied loads of 100 μN and e-beam irradiation while varying $V_A$ and $J$ from 1 to 30 kV and 0.43 to 27.94 A/m², respectively (Table S1). SEM images of the amorphous silica nanospheres after compression (Fig. 2(a)) clearly show that an e-beam with higher $V_A$ or $J$ results in larger plastic deformation of the nanosphere during compression. The compressed shapes of the nanospheres at 1 kV, 0.43 A/m² e-beam (first column or row of the SEM images in Fig. 2(a)) are similar to the shape obtained without irradiation (Fig. 1(a-3)). The SEM images enclosed in the red box in Fig. 2(a) show that as $V_A$ or $J$ increases, the compressed nanosphere gradually forms a disk shape. However, a quantitative analysis of the compression load–depth curves shown in Fig. S10 reveals the unique $V_A$ and $J$ dependencies of the plastic deformation of the amorphous silica nanospheres. Considering the self-similarity of the nanospheres, we calculated the nominal flow stress (dividing the compression load by $\pi r^2$) at 0.1 nominal strain (i.e., where the compression depth is 10% of the sphere diameter) from the compression load–depth curves. The normalized flow stress ($\xi_\sigma$) was calculated by dividing the nominal flow stress under each e-beam condition ($\sigma$) by that without irradiation ($\sigma_{\text{beam-off}}$) as follows:

$$\xi_\sigma = \frac{\sigma}{\sigma_{\text{beam-off}}}$$

which represents the flow stress change due to the e-beam. For example, under beam-off conditions, the $\xi_\sigma$ of the amorphous silica...
nanosphere should equal 1 and as \( \xi_\sigma \) decreases, plastic deformation during compression increases.

Our quantitative analysis based on the \( \xi_\sigma \) versus \( J \) plots at different \( V_A \) values (Fig. 2(b)) yields three major findings. First, a \( V_A \) threshold exists, above which e-beam irradiation induces plastic deformation. Without irradiation, \( \xi_\sigma = 1 \pm 0.12 \) (black square in Fig. 2(b)). Under e-beam irradiation at \( V_A > 1 \) kV, \( \xi_\sigma < 1 \) (orange, gold, green, light-blue, blue, and purple squares in Fig. 2(b)) and \( \xi_\sigma = 1 \) only at \( V_A = 1 \) kV (red squares in Fig. 2(b)). Thus, \( V_A \) should exceed 1 kV to induce plastic deformation of amorphous silica nanospheres. Second, \( \xi_\sigma \) does not decrease monotonically with \( J \) and plateaus at \( J > 6.98 \) A/m²; for example, at \( V_A = 5 \) kV, \( \xi_\sigma \) initially decreases as \( J \) increases and then plateaus at \( \xi_\sigma = 0.33 \) (green squares in Fig. 2(b)). Thus, the nanospheres experience similar plastic deformation when \( J > 6.98 \) A/m². This trend was also observed for other values of \( V_A \) (i.e., 2, 3, 10, 20, and 30 kV), as shown in Fig. 2(b). Finally, the nanospheres experienced maximum plastic deformation at \( V_A = 5 \) kV. At every value of \( J \) (except 0.43 A/m²), \( \xi_\sigma \) decreases when \( V_A \) exceeds 1 kV, but reaches the minimum at \( V_A = 5 \) kV (green square in Fig. 2(b)). At \( V_A = 5 \) kV and \( J = 27.94 \) A/m², \( \xi_\sigma = 0.32 \), indicating that the flow stress is 68% less than that without irradiation. When \( V_A \) exceeds 5 kV, \( \xi_\sigma > 0.32 \), and \( \xi_\sigma \) at \( V_A = 30 \) kV (purple squares in Fig. 2(b)) is comparable to that at \( V_A = 3 \) kV (gold squares in Fig. 2(b)). Previous research regarding e-beam irradiation damage of materials indicates that the damage increases with increasing particle energy, which correlates with the power of the e-beam [34,35]. In this context, we initially observed that the ductility should monotonically increase with increasing \( V_A \) and \( J \) of the e-beam. Therefore, our observation of optimal values of \( V_A \) and \( J \) that maximize the ductility of the amorphous silica nanospheres could be seen as counterintuitive. However, simulation of the electron–matter interaction offers insights into these findings.

3.2. Role of electron–mater interaction during e-beam-induced plastic deformation

When a solid material is irradiated with accelerated electrons, the interaction between the electrons and matter often leads to changes in the material properties [36,37]. The electron–matter interaction can be described using a Monte Carlo simulation based on elastic and inelastic scattering events [38,39]. Fig. 3 (a) shows a model simulating the interaction during a single line scan by the e-beam across an amorphous silica nanosphere, where the green arrows and line indicate the line-scan profile of the e-beam. During elastic collisions, the incident electrons can be transmitted in or reflected from the material. Alternatively, through inelastic collisions, the incident electrons transfer energy to the solid matter. The transferred energy has the potential to change the nature of the interatomic covalent bonds, making them switchable. As the Monte Carlo model simulates the energy and trajectory of incident electrons, we obtained the total energy that the system absorbs during inelastic scattering and the total volume of the region where inelastic scattering occurs. Accordingly, we investigated whether these two values explain the experimental findings concerning the relationship between the plastic deformation of the amorphous silica nanospheres and the \( V_A \) and \( J \) of the scanning e-beam.

First, the total absorbed energy \( (E_{\text{total}}) \) does not explain the maximum plastic deformation of amorphous silica observed under 5 kV, 27.9 A/m² e-beam. Fig. 3(b) shows the \( E_{\text{total}} \) with respect to \( J \) at different \( V_A \) values. The trend of \( E_{\text{total}} \) observed under the respective e-beam conditions is very different to that of \( \xi_\sigma \) shown in Fig. 2(b). For example, \( E_{\text{total}} \) is proportional to \( J \) at every \( V_A \), whereas \( \xi_\sigma \) is inversely proportional to \( J \) and then becomes constant at \( J > 6.98 \) A/m². In addition, at every \( J \), the highest and lowest \( E_{\text{total}} \) values are observed at \( V_A = 3 \) and 30 kV, respectively, and the values differ by one order of magnitude (gold-gray and purple-gray squares in Fig. 3(b)). Conversely, at \( V_A = 3 \) and 30 kV, \( \xi_\sigma \) is almost constant for all \( J \) values (purple and gold squares in Fig. 2(b)). Moreover, \( E_{\text{total}} \) at \( V_A = 10 \) kV is comparable to that at 1 kV, which is inconsistent with the \( V_A \) threshold determined for plastic deformation (light blue-gray and red-gray squares in Fig. 3(b), respectively). The distribution of absorbed energy \( (E_s) \) also deviates from the deformation trends observed in the \( \text{in-situ} \) experiments of the amorphous silica nanospheres. The energy distributions along and normal to the single line-scan profile of the e-beam shown in Fig. 3(c) indicate that most of the energy is absorbed at the surface. For 3 kV, 279 A/m² e-beam (intersections of second row and third and sixth columns in Fig. 3(c)), \( E_s \) at the irradiated surface is almost 10-times larger than that 50 nm beneath the surface. If the plastic deformation is directly related to \( E_s \), most deformation should occur at the irradiated surface, and the deformed shape should be asymmetric. However, during the actual experiment under the same e-beam conditions, the nanosphere was compressed symmetrically (intersections of fourth row and third column in Fig. 2(a)). The apparent disconnect between \( E_s \) and \( \xi_\sigma \) indicates that the plastic deformation of the nanosphere does not simply depend on the energy absorbed from the e-beam.

In contrast, the interaction volume (\( \Omega_i \)), i.e., the entire volume of the region where the energy absorption occurs via inelastic scattering, correlates very strongly with \( \xi_\sigma \). This is illustrated by the non-interaction volume fraction (\( f_{\text{GN}} \)), which is defined as:

\[
f_{\text{GN}} = \frac{\Omega_{\text{NI}}}{\Omega_i} = \frac{\Omega_{\text{ NI}} - \Omega_i}{\Omega_i} \quad (4)
\]

where \( \Omega_{\text{NI}} \) and \( \Omega_i \) indicate the volume of the nanosphere and the non-interaction volume within the sphere (where the energy absorption does not occur), respectively. For example, without irradiation, the \( f_{\text{GN}} \) of the nanosphere should be 1 and \( f_{\text{GN}} \) decreases as \( \Omega_i \) increases. The \( f_{\text{GN}} \) versus \( J \) plots at different \( V_A \) values shown in Fig. 3(d) show three characteristics, which are very similar to the findings derived from \( \xi_\sigma \) versus \( J \) plots (Fig. 2(b)). First, \( f_{\text{GN}} \) = 0.95 ± 0.03 at \( V_A = 1 \) kV, regardless of \( J \), which is the same as that without irradiation (red squares in Fig. 3(d)). Second, except at \( V_A = 1 \) kV, \( f_{\text{GN}} \) decreases at every \( V_A \) with increasing \( J \) and then plateaus at \( J > 6.9 \) A/m². Third, among the various \( V_A \) values, the lowest \( f_{\text{GN}} \) is observed at \( V_A = 5 \) kV. The characteristic dependencies of \( f_{\text{GN}} \) on \( V_A \) and \( J \) are surprisingly similar to those of \( \xi_\sigma \), i.e., the plastic deformation of the nanosphere. Simulated cross-sectional images of \( \Omega_i \) along and normal to the single line-scan profile of the e-beam shown in Fig. 3(e) provide a physical explanation of the correlation between \( f_{\text{GN}} \) and \( \xi_\sigma \). First, at \( V_A = 1 \) kV, \( f_{\text{GN}} \approx 1 \) because the incident electrons penetrate only 40 nm (losing all energy). In addition, the \( \Omega_i \) cross-sections show that only a limited volume of matter (orange region) near the irradiated surface interacts with the incident electrons. As there is no change in the deformation behavior of the region where the interaction does not occur, \( \xi_\sigma \) at \( V_A = 1 \) kV is similar to that without irradiation. Second, the constant \( f_{\text{GN}} \) at \( J > 6.9 \) A/m² is due to the saturation of \( \Omega_i \) inside the nanosphere. This is explained by comparing the \( \Omega_i \) cross-sections along the single line-scan profile of the e-beam at \( J = 1.8, 6.9, \) and 279 A/m² in Fig. 3(e). At \( J \leq 6.9 \) A/m², \( \Omega_i \) expands with increasing \( J \) at every \( V_A \). Notably, at \( J > 6.9 \) A/m², \( \Omega_i \) already covers most of the volume of the sphere from the surface to the bulk into which the incident electrons can penetrate. A further increase in \( J \) does not increase \( \Omega_i \), and thus, \( \xi_\sigma \) does not decrease further but remains constant. Third, among the various \( V_A \) values, the lowest \( f_{\text{GN}} \) is observed at \( V_A = 5 \) kV because the incident electrons are scattered and radially spread inside the nanosphere, resulting in interactions occurring throughout most of \( \Omega_{\text{NI}} \). This is attributed to the increasing penetration depth.
and decreasing scattering angle of the electrons as $V_A$ increases. At $V_A > 1$ kV, $f_{2\text{NI}}$ decreases because the incident electrons penetrate deeper into the nanosphere. Further, the $\Omega_2$ cross-sections at $V_A = 3$ kV and $J = 27.9$ A/m² (intersections of the second row with the third and sixth columns in Fig. 3(e)) show that the interaction occurs up to a depth of 140 nm from the irradiated surface. In particular, at $V_A = 5$ kV, the incident electrons have sufficient energy to pass through the nanosphere. Therefore, $\Omega_2$ at $V_A = 5$ kV and $J = 27.9$ A/m² covers both the cross-section along and normal to the single line-scan profile of the e-beam (intersections of the third row with the third and sixth columns in Fig. 3(e)), and the corresponding $f_{2\text{NI}}$ is minimized, becoming as small as 0.04. The increase in $\Omega_2$ with $V_A$ makes the nanosphere more ductile and eventually $\varepsilon$ decreases. However, any further increase in $V_A$ decreases $\Omega_2$, resulting in $f_{2\text{NI}}$ increasing at $V_A > 5$ kV, because the incident electrons can pass through the sphere with a narrower scattering angle. This is indicated by the $\Omega_2$ cross-sections at $V_A = 5$, 10, and 30 kV shown in Fig. 3(e). At $J = 27.9$ A/m², the $\Omega_2$ at $V_A = 5$, 10, and 30 kV generally covers the whole cross-section along the single line-scan profile of the e-beam, indicating that the penetration depth is larger than the nanosphere diameter (intersections of the third to fifth rows with the third column in Fig. 3(e)). However, in the cross-section normal to the single line-scan profile of the e-beam, $\Omega_2$ gradually decreases as $V_A$ increases from 5 to 30 kV (intersections of the third to fifth rows with the sixth column in Fig. 3(e)). This is because the incident electrons accelerated at 5 kV deviate significantly from their original trajectories during scattering and radially spread inside the nanosphere. In contrast, the incident electrons accelerated at 10 and 30 kV deviate from their original trajectories at relatively small angles dur-
ing scattering and narrowly penetrate towards the opposite side of the sphere. Subsequently, $\Omega_A$ (denoted in white) increases in the cross-section normal to the single line-scan profile of the e-beam at $V_A > 5$ kV, which corresponds to an increase in $\xi_\sigma$. The strong correlation between $\Omega_A$ and $\xi_\sigma$ suggests that the counter-intuitive $V_A$ and $J$ dependencies of the plastic deformation of the amorphous silica nanosphere may be ascribed to the trajectories of the incident electrons and the resulting $\Omega_A$. This also explains why the focused SEM e-beam induces plastic deformation despite having a much smaller beam spot than that used in previous CTEM e-beam studies.

33. Athermal deformation of amorphous silica under e-beam irradiation

The deformation behavior of an amorphous silica pillar, wherein a uniform stress field develops during compression, also depends heavily on $\Omega_A$. The fabricated micropillars (diameter of 280 nm and height of 900 nm) were subjected to in-situ compression tests with a 500 nm-radius flat punch indenter under no irradiation or various e-beam conditions (2 kV, 1.6 A/m²; 5 kV, 1.4 A/m²; 18 kV, 2.0 A/m²; and 30 kV, 2.4 A/m²²) and the $\xi_\sigma$ values were compared with the corresponding $f_{\text{FN}}$ values calculated using Monte Carlo simulations (Figs. 4 and S11). The model simulates the interactions inside the micropillar induced by the single line scan of SEM e-beams with $V_A = 2$, 5, 18, or 30 kV and $J = 1.8$ A/m² (Fig. 4(a)). Fig. 4(b) shows the $\xi_\sigma$ values obtained by the in-situ compression tests of the micropillar and the $f_{\text{FN}}$ values. The $\xi_\sigma$ and $f_{\text{FN}}$ of the micropillar showed similar trends, which are consistent with those observed for the nanospheres. The $\xi_\sigma$ and $f_{\text{FN}}$ minima of the micropillar are observed at $V_A = 5$ kV. The $\Omega_A$ cross-sections (Fig. 4(c)) show that the smallest $f_{\text{FN}}$ (largest $\Omega_A$) occurred at $V_A = 5$ kV due to the increased penetration depth and scattering angles of the incident electrons at the optimal $V_A$. This suggests that the plastic deformation of amorphous silica occurs under e-beam irradiation regardless of the geometry or fabrication methods of the silica nanostructures.

The pillar compression test explains the deformation of amorphous silica when inelastic scattering of incident electrons occurs within the material. We investigated the strain rate sensitivity ($m$), which is a parameter of the deformation mechanism of a material [40–42], and is defined as:

$$m = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}}$$

where $\sigma$ is the nominal flow stress at 0.1 nominal strain and $\dot{\varepsilon}$ is the strain rate. For amorphous materials, $m = 0$ indicates a rigid plastic material, whereas $m = 1$ indicates a linear viscous solid [41,42]. To calculate the $m$ of amorphous silica under e-beam irradiation, we conducted in-situ compression tests on micropillars by varying $\dot{\varepsilon}$ from $6.7 \times 10^{-4}$ to $1.4 \times 10^{-2}$ s⁻¹ under no irradiation or e-beam conditions of 2 kV, 1.6 A/m²; 5 kV, 1.4 A/m²; and 18 kV, 2.0 A/m²² (Fig. S12).

The micropillar interacting with the incident electrons undergoes viscoplastic deformation, as shown by the slopes (i.e., $m$) of the $\sigma$–$\dot{\varepsilon}$ curves under various e-beam conditions (Fig. 5 (a)). Without irradiation, the deformation of the pillar is mostly rigid plastic. The black squares and dotted line shown in Fig. 5(a) indicate that $\sigma$ is almost independent of $\dot{\varepsilon}$ and the corresponding $m$ is as small as $5.98 \times 10^{-3}$, which is consistent with the results of other studies conducted under ambient conditions [42–44]. Under e-beam irradiation, the deformation becomes viscoplastic. Under 2 kV, 1.6 A/m²; 5 kV, 1.4 A/m²; and 18 kV, 2.0 A/m²² e-beams, $\sigma$ increases with increasing $\dot{\varepsilon}$ (respectively denoted by the orange, green, and blue squares in Fig. 5(a)). The $m$ values under 2 kV, 1.6 A/m² and 18 kV, 2.0 A/m²² e-beams increased to $7.93 \times 10^{-2}$ and $1.77 \times 10^{-1}$, respectively (orange and blue dotted lines in Fig. 5(a)). Under a 5 kV, 1.4 A/m² e-beam, $m$ is $2.71 \times 10^{-1}$ (green dotted line in Fig. 5(a)), which is a dramatic 45-fold increase compared with the non-irradiated condition. Therefore, amorphous silica deforms viscoplastically during compression. The activation volume ($V^*$), i.e., the volume of an atom cluster migrating during deformation, supports this conclusion. Based on the $m$ analysis, we calculated $V^*$ as follows:

$$V^* = \sqrt{3kT} \left( \frac{\partial \ln \dot{\varepsilon}}{\partial \sigma_m} \right)$$

where $k$ is Boltzmann's constant and $T$ is the temperature. Lower $V^*$ values of an amorphous material indicate a higher degree of viscoplastic deformation. We assumed $T = 298$ K because there is almost no temperature increase induced via e-beam irradiation, as shown later. Fig. 5(b) shows the $\dot{\varepsilon}$–$\sigma$ curves of the micropillars under various e-beam conditions with the corresponding $V^*$ values. With no e-beam irradiation, $V^*$ is $\sim 138.26$ Å³, which is consistent with the $V^*$ at ambient temperature [43]. Under e-beam irradiation, $V^*$ decreases drastically. In particular, under a 5 kV and 1.4 A/m² e-beam, $V^*$ is 9.64 Å³, which corresponds to an atom cluster consisting of 2–3 atoms (or approximately one molecular formula unit). This $V^*$ value is consistent with that at high tem-
perature [45–47]. The viscoplastic deformation of amorphous material occurs at temperatures exceeding \( T_g \) (1200°C for amorphous silica), because interatomic bond switching, which is a key mechanism of such deformation, is thermally activated [16,48]. Therefore, this raises the question of whether the ductile plastic deformation of amorphous silica under e-beam irradiation is caused by beam-induced heating, which is an electron–matter interaction mechanism that must be considered.

Depending on \( V_A \), incident electrons can affect the mechanical properties of materials in three ways via elastic and inelastic scattering. First, a charged particle can produce vacancies in material via elastic scattering. To trigger this event, the maximum transferable kinetic energy from the charged particle to the atom should be larger than the atomic displacement energy. However, this vacancy-formation mechanism, or so-called knock-on damage, is impossible under the \( V_A \) conditions used here because it requires incident electrons accelerated at hundreds of kilovolts [16–18,26,34]. In addition, heating or radiolysis (electron excitation) can occur due to inelastic scattering. Certainly, e-beam-induced heating occurs via electron–phonon scattering, but the temperature does not increase enough to induce viscoplastic deformation under e-beam irradiation in the studied micropillars based on the following experiments and simulations. This was confirmed in several ways.

First, no thermal expansion of a micropillar was observed under 5 kV e-beam irradiation (the detailed method is described in the Supplementary Materials, Fig. S13). The micropillar should show a thermal expansion of approximately 30 nm at the \( T_g \) of 1200°C. Second, there was no morphological change induced by the e-beam in a low-melting-temperature Bi thin film (271°C) deposited on an amorphous silica substrate (see Supplementary Materials and Fig. S14 for details). This Bi thin film showed a dewetting-like behavior and hence, the morphology changed when heated at 450°C under vacuum condition (Fig. S14 (a-c)). When the 5 kV, 1.4 A/m² e-beam was used to irradiate the Bi-coated micropillar, no apparent change in the morphology of this thin film was observed (Fig. S14 (d-f)). In contrast, when the same pillar was subsequently heated at 450°C under a vacuum, the film clearly agglomerated (Fig. S14 (g)). These findings suggest that the temperature of the micropillar under e-beam irradiation was far below the \( T_g \) of amorphous silica. Finally, through finite element analysis, we estimated the temperature increase in a micropillar under 5 kV, 1.4 A/m² e-beam based on the \( E_{\text{total}} \). In it, the temperature rise is <1°C, which is consistent with that estimated by the approach in previous study [16] (Detailed information is described in Supplementary Materials, Fig. S15). These indirect analyses suggest that heating via e-beam irradiation is not the core mechanism of viscoplastic deformation of amorphous silica observed in this study.

Radiolysis may also be induced by the e-beam, where the interatomic bonds are altered by emitting excited electrons through the interaction with incident electrons accelerated by a few to tens of kilovolts, leading to ionization and secondary-electron emission [26,34]. The Monte Carlo simulation results indicate that the incident electrons with low \( V_A \) values of 1–30 kV yield secondary electrons within the micropillar (Fig. S16), suggesting that the radiolytic mechanism could occur, where the nature of the interatomic bonds could change. Atomic scale simulation can provide a rough estimation of bonding nature change in the amorphous silica. Through density functional theory calculations with Vienna Ab initio Simulation Package (VASP), we confirmed that when the excess electrons or holes, which can be generated by the electron–matter interaction, are introduced to the amorphous silica, Si-O bond breaking possibly occurs (Fig. S17). It suggests that the electron-matter interaction weakens the interatomic bond.

In summary, the incident electrons accelerated by 1–30 kV generate excited electrons in the amorphous silica through electron–matter interactions. The incident and excited electrons alter the nature of interatomic bonding, makes the Si–O bonds more switchable, whereby the amorphous silica becomes ductile and undergoes viscoplastic deformation analogous to thermally activated viscoplastic deformation. Therefore, the viscoplastic deformation of amorphous silica strongly depends on the volume of the region where the electron–matter interaction occurs; that is, \( \Omega_r \), not \( E_a \). It should be noted that e-beam induced plasticity depends on the bonding types and atomic structures of materials. For instance, the previous in-situ studies of metallic nanomaterials reported no e-beam-induced deformation, even under e-beams accelerated by hundreds of kV [49–53]. Even in other crystalline ceramic materials such as silicon, sapphire, and MgO [54,55], there was no noticeable viscoplastic deformation behavior under the e-beam irradiation. Hence the dramatic brittle to viscoplastic transition in amorphous silica induced by the e-beam irradiation is likely to be a unique phenomenon resulting from its glassy structure with covalent bonding nature.

3.4. Effect of electron–matter interaction volume on mechanical shaping

The discovery of e-beam-induced deformation of brittle amorphous silica may offer a new approach to mechanical shaping of this material. We successfully modeled the forming behaviors of various shapes in amorphous silica using scanning e-beam irrada-
Fig. 6. Determination of the mechanical properties of amorphous silica during interaction with incident electrons and in the absence of incident electrons. (a) Experimental (denoted by lines) and computational (denoted by sequences of squares) compression load-displacement curves under beam-off (black) and 5 kV, 27.9 A/m² e-beam (green) conditions. (b) Corresponding experimental and simulated compressed shapes under beam-off (enclosed in black box) and 5 kV and 27.9 A/m² e-beam conditions (enclosed in green box).

Fig. 7. Mechanical shaping of fused quartz pillar by controlling electron-matter interaction volume under 5 kV, 913 A/m² (green), and 30 kV, 1606 A/m² (purple) e-beam conditions. (a) Interaction volume within the fused quartz pillar under each set of electron-beam conditions. Schematic diagram of interaction model (top) and cross-section view of interaction volume (bottom). (b) Compression load-depth curves of fused quartz pillar obtained experimentally (lines) and through simulation (lines with open squares). (c) Compressed shape of fused quartz pillar obtained experimentally (left) and through simulation (right).

tion using FE analysis. First, we determined the mechanical properties of the amorphous silica for constitutive equations, during full interaction with incident electrons (5 kV, 27.9 A/m²) and in the absence of incident electrons (beam-off), via fitting of the experimental data (Fig. 6). Then, we treated the amorphous silica subjected to scanning e-beam irradiation as a composite of Ω²₁ and Ω₁. For instance, we modeled the localized shape-formation behavior of amorphous silica in which a volume fraction of the material interacts with incident e-beams with different conditions. The Monte Carlo simulation results in Fig. 7(a) show that a volume fraction of a micropillar interacts with the incident electrons when a limited area of the micropillar is irradiated with 5-kV, 913-A/m² (enclosed in the green box) and 30 kV, 1606 A/m² (enclosed in the purple box) e-beams, respectively. Due to the difference in scattering angle, Ω₁ under the former conditions is greater than that under the latter conditions. Under a 5 kV, 913 A/m² e-beam, f₁(0.19) is 2.53 times less than that under a 30 kV, 1606 A/m² e-beam (0.48). Consistent with Ω₁ results, the micropillar becomes softer and undergoes greater viscoplastic deformation under the 5 kV, 913 A/m² e-beam. We confirmed this through in-situ compression testing of a micropillar with a reduced rectangular-shaped area subjected to e-beam irradiation (Fig. S18). As shown in the compression load–depth curves in Fig. 7(b), the volume of the micropillar under a 30 kV, 1606 A/m² e-beam (purple curves) are higher than those
under a 5 kV, 913 A/m² e-beam (green curves) at every compression depth. Furthermore, due to $\Omega_2$, there is a significant difference between the compressed shapes of the micropillars. The SEM images in Fig. 7(c) show that, under a 30 kV, 1606 A/m² e-beam, intensive viscoplastic deformation occurs around the irradiated area (left SEM image, purple box). In contrast, under a 5 kV, 913 A/m² e-beam, viscoplastic deformation occurs throughout the whole micropillar (left SEM image, green box). We modeled these compression load–depth curves and deformed shapes of the micropillars based on the mechanical properties of $\Omega_{NI}$ and $\Omega_2$. We assumed that the mechanical properties of $\Omega_2$ under both beam conditions were the same because $f$ is large enough to induce saturated softening behavior, as shown by Fig. 2(b). Hence, we incorporated these properties into the $\Omega_{NI}$ and $\Omega_2$ in the FE model estimated based on the Monte Carlo simulation for each e-beam condition. Consequently, in Fig. 7(b), the simulated compression load–depth curves under a 30 kV, 1606 A/m² e-beam (denoted by a purple line with open squares) and a 5 kV, 913 A/m² e-beam (denoted by a green line with open squares) match the experimental results quite well. The simulated deformed shapes also describe the plastic deformation concentrated along $\Omega_2$. The deformed shapes under both e-beam conditions (right images enclosed in purple and green boxes in Fig. 7(c)) result from significant viscoplastic deformation concentrated in $\Omega_2$.

The experimental and computational analysis of the deformation behavior of amorphous silica nanoshells under e-beam irradiation further validated our approach, and also suggested a nanomaterial size dependency. It is expected that if the material volume is small enough for the incident electrons to penetrate, the amorphous silica can undergo ductile plastic deformation under e-beam irradiation with a very low $V_A$. Hollow nanoshells with a diameter of 280 nm and nanoshell thickness of 20 nm (Fig. S19) were fabricated and their deformation behavior was investigated under a 1 kV, 6.9 A/m² e-beam irradiation. It should be noted that the amorphous silica nanosphere does not show viscoplastic deformation under such conditions due to the small interaction volume relative to the material volume (Fig. 2 and 3). As shown in Fig. 8 (a), Monte Carlo simulation results suggest that the $\Omega_2$ induced under a 1 kV, 6.9 A/m² e-beam conditions encompasses the entire nanoshell structure because the thin shell allows the penetration of incident electrons accelerated by such low voltage. As expected, under beam-off conditions, the deformation of the spherical nanoshell ends with an abrupt load drop (black curve in Fig. 8(b)) and cracks were formed on the upper surface of the spherical nanoshell (left SEM image enclosed in the black box in Fig. 8(c)). In contrast, under the 1 kV, 6.9 A/m² e-beam, the spherical nanoshell accommodates significant viscoplastic deformation and continuously deforms up to a compression depth of 150 nm (red curves in Fig. 8(b)), producing a donut-like shape without any surface cracking (left SEM image in a red box, Fig. 8(c)). Critically, this plastic deformation of the nanoshell under a 1 kV, 6.9 A/m² e-beam irradiation suggests that the e-beam-induced deformation is specimen-size dependent. We also demonstrate that our simulation approach successfully models this e-beam-induced plastic deformation of the spherical nanoshell. The compression load–depth curves obtained through FE simulation with the same mechanical properties of $\Omega_{NI}$ and $\Omega_2$ (black and red lines with open squares in Fig. 8(b)) correspond well with the experimental results under beam-off and 1 kV, 6.9 A/m² e-beam conditions, respectively (black and red curves in Fig. 8(b), respectively). Furthermore, the simulated deformed shapes are similar to those observed by SEM. Cross-sectional im-
ages show that the spherical nanoshell accommodates deformation through inward bending of the top surface and outward bending of the side surfaces. Under beam-off conditions, the deformation ends with crack formation after minimal bending of these surfaces (right image enclosed in black box in Fig. 8(c)). Under e-beam irradiation, severe bending of these surfaces is possible, producing the toroidal deformed shape (right image enclosed in red box in Fig. 8(c)).

Finally, we show that much more complex shaping, similar to that achieved by actual bulk-scale glass crafting techniques, is also possible. To do so, we conducted nanoforging of a spherical amorphous silica nanoshell by pushing it into a nanotrench, fabricated on a sapphire substrate, with a Pt nanomanipulator. A series of snapshots in Fig. 8(d) clearly shows that the nanoforging of the spherical nanoshell is possible under e-beam irradiation. Without any brittle fracture, the upper and lower surfaces of the spherical nanoshell are deformed by the manipulator and the trench, respectively. In addition, considering $\Omega_2$, we accurately modeled this mechanical shaping behavior, which is analogous to that induced during typical glass crafting. Fig. 8(e) shows how the spherical nanoshell deforms during the nanoforging under e-beam irradiation. The model specifically describes the deformation of the spherical nanoshell by the nanomanipulator and nanotrench, and suggests that the complex mechanical shaping of amorphous silica under e-beam irradiation is predictable and controllable. In this regard, this study could be a breakthrough in silica glass industries for small-scale devices where the temperature-dependent formability of amorphous silica currently limits the process compatibility and product geometry. With a considered e-beam irradiation design, we can improve the formability of silica glass at room temperature and widen its former geometric range compared to conventional processes such as the float glass process, lithography, etching, and deposition. Moreover, our main finding that electron-matter interactions can change the nature of strong Si–O covalent bonds could be applicable to other covalently bonded nonmetallic materials. Accordingly, we believe this study has enormous potential for the development of e-beam-assisted manufacturing processes for nonmetallic materials.

4. Conclusions

We investigated the ductile plastic deformation of amorphous silica under SEM e-beam irradiation at low $V_A$ values. Remarkably, the ductility of amorphous silica is not simply proportional to the $V_A$ and $J$ of the e-beam, and there are optimal values at which e-beam irradiation maximizes ductility. This is related to the trajectories of the incident electrons and the $\Omega_1$ generated within the amorphous silica. The electron-matter interaction changes the nature of the Si–O interatomic bonding, which enables thermal deformation of amorphous silica. We thus modeled the mechanical shaping of various amorphous silica structures under e-beam irradiation. Our models accurately predict the responses of the material to external forces, in addition to the final deformed shapes under e-beam irradiation. Accordingly, we demonstrated the viability of mechanically shaping small-scale amorphous silica under e-beam irradiation. This model may provide guidance in engineering e-beam-induced mechanical shaping utilizing existing e-beam technology in manufacturing brittle silica glass on a small scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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