



Energy-saving windows derived from transparent aerogels

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ABSTRACT

Energy-saving windows play a crucial role in sustainable development of green buildings. Integrating super-insulating aerogels with glasses is an attractive method to minimize the energy loss through building windows. However, achieving energy-saving windows with high transparency, super insulation, mechanical robustness, low cost, and scalable aerogels remains a challenge. In a recent study published in *Nature Energy*, Smalyukh and coworkers synthesized a highly transparent silanized cellulose aerogel for energy-saving windows, overcoming the challenges. This work promotes the practical application of aerogel-based glazing and provides an effective way to save energy of buildings.

KEYWORDS

transparent aerogels, windows, super insulation, mechanical robustness

The energy consumption of commercial and residential buildings accounts for about 40% of global energy, and most energy is consumed by heating, cooling, and ventilation. The energy loss through windows is as much as 60% of total energy consumption of buildings owing to the poor thermal insulation of windows [1]. The window technologies that can minimize the heat transfer between interior and exterior are beneficial to reduce the energy loss, such as thick glass, multi-pane glass with filled gases, low-emittance coating, anti-reflective coating, and insulating glass with super-insulating materials [2]. Nevertheless, increasing the thickness of glass will result in the high cost and weight of windows. The application of multi-pane glazing with xenon, krypton, argon, air or vacuum is limited by gas convection, seal integrity, and high costs. The low-emittance coating and anti-reflective coating-based glazing can hamper the heat transfer, but at a cost of the deterioration of the visible-range transparency. Therefore, it's imperative to explore advanced and appropriate insulating materials for windows with the aim of reducing the energy loss.

Integrating aerogels with glasses is an attractive method to minimize the energy loss through building windows owing to super insulation and lightweight. However, aerogels suffer from the brittle and breaks, limiting the extensive applications in energy-saving windows. To break the bottleneck, Lennart Bergström et al. synthesized a nanocellulose and graphene oxide-based aerogel, exhibiting high axial specific Young's modulus of 77 kNm/kg and ultralow radial thermal conductivity of 15 mW/m-K, much lower than standing air (26 mW/m-K) [3]. Zhao et al. proposed a strong mesoporous silica aerogel interpenetrated with a silylated nanocellulosic scaffold, showing 55% and 126% increase in Young's

modulus and tensile strength while maintaining super-insulating properties (<20 mW/m-K) [4]. To overcome the large-volume application of fiber and binders in the mechanical reinforcement of silica aerogel, they further presented a direct ink writing protocol to create miniaturized silica aerogel with lower thermal conductivity of 15.9 mW/m-K and excellent mechanical robustness [5].

The above-mentioned aerogels exhibit super-insulating properties and enhanced robustness, which can be used to integrate with glasses for commercial applications. However, these aerogels are not suitable for conventional windows due to low transparency in visible-range. In other words, achieving simultaneously highly transparent, super thermal insulating, mechanically robust, low cost, and scalable aerogel-based glazing remains a great challenge.

Recently, Smalyukh and coworkers innovatively synthesized a highly transparent silanized cellulose aerogel (SiCellA) with ultra-low thermal conductivity, excellent mechanical robustness, and super hydrophobicity by utilizing colloidal self-assembly and supercritical drying [6]. A thin film of proposed SiCellA can be readily adhere to the inner surface of pre-existing single-pane window with the help of electrostatic charging, as shown in Fig. 1(a). It can also be inserted into the gap between the multi-pane insulating glass units (IGU) to further boost the thermal barrier performance of windows (Fig. 1(b)). A practical window product of double-pane IGUs with a SiCellA film attached to one surface is displayed in Fig. 1(c).

Figure 1(d) describes the SiCellA's poor thermal conductivity at different porosities and temperatures, ranging from 15.25 to 31.06 mW/m-K. The thermal conductivity increases as the temperature

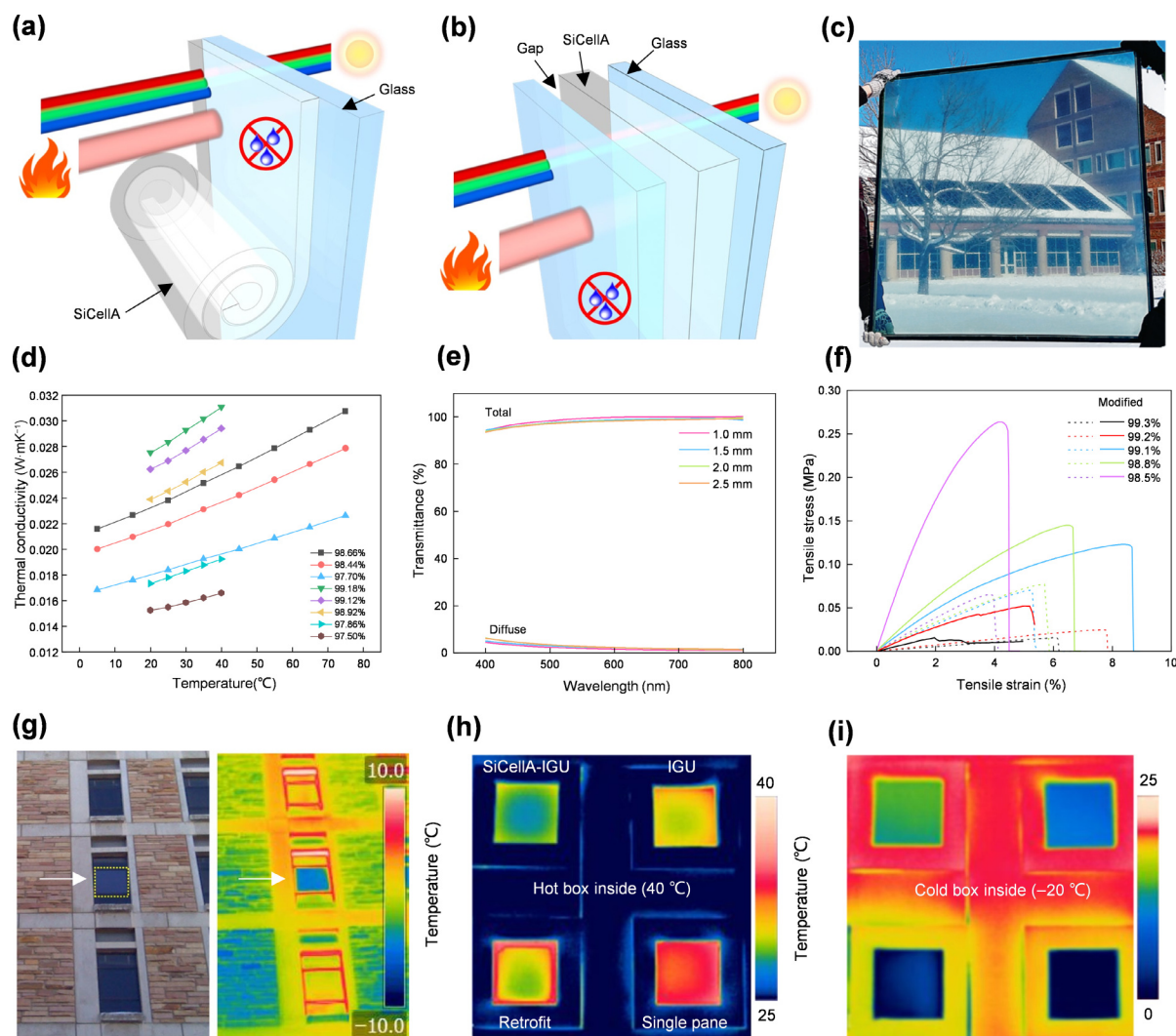


Figure 1 Energy-saving windows derived from SiCellA transparent aerogel films. (a) Schematic drawings of a window retrofitted with a SiCellA film. (b) Schematic drawings of IGUs with a SiCellA film inserted between glass panes. (c) Photos of double-pane IGUs with 3 mm-thick SiCellA films attached to one surface of glass panes. (d) Temperature dependence of thermal conductivity of SiCellA at different porosities. (e) Visible-range spectral dependence of SiCellA films with different thicknesses. (f) Tensile stress–strain dependence of silanized (solid lines) and unmodified (dashed lines) aerogels with different porosities. (g) Single-pane window retrofitted with a 72.1 cm × 71.4 cm SiCellA film and photographed from outside with both a regular photo camera (left) and a thermal imaging camera (right). (h) Infrared thermal imaging photos of different types of fenestration mounted in the openings of 0.78 m × 0.68 m × 0.43 m hot boxes with the inside temperature set at 40 °C. “SiCellA-IGU” marks a double-pane IGU with a SiCellA aerogel film; “IGU” marks a double-pane IGU without SiCellA; “Retrofit” marks a single 3 mm-thick glass pane retrofitted with a SiCellA film; “Single pane” marks a single 3 mm-thick glass pane. (i) Infrared thermal imaging photos of different types of fenestration mounted in the openings of 0.78 m × 0.68 m × 0.43 m cold boxes with the inside temperature set at –20 °C. Reproduced with permission from Ref. [6] © Abraham, E. et al. 2023.

increasing. Generally, the thermal conductivity of porous materials is mainly determined by gas conduction and solid conduction [7]. According to Knudsen effect, the contribution of gas conduction decreases significantly if the pore size becomes smaller than the mean free path of air molecules. The inter-fiber pores of SiCellA are typically smaller than 100 nm, promoting the collision between air molecules and SiCellA surface. Consequently, it partly hinders the thermal conduction via deteriorating the continuity of air transportation. The thermal conductivity contributed by gas conduction improves with enlarging the porosity. In addition, heat conduction of solids in electric-insulating cellulose mainly depends on phonons. For phonons, covalent bonds favor heat transfer and weaker bonds such as hydrogen and van der Waals hamper the phonons transfer [7]. The nanofiber in SiCellA is interlinked by hydrogen bonds between carboxyl groups, leading to weak heat transfer. Moreover, the thin fibers and poor contacts between them strongly induce the phonons scattering at the

solid/gas and solid/solid interfaces, resulting in low thermal conduction. Thus, the thermal conductivity contributed by solid decreases with increasing the porosity. In a word, these two factors synergistically contribute to the poor thermal conductivity of SiCellA.

Besides super thermal insulation, the SiCellA exhibits high transparency simultaneously. The visible-range transmissivity achieves up to 97%–99% and the haze is as low as 1%–3% at different thicknesses, as shown in Fig. 1(e). Conventionally, the porous structure of bundles and clusters of nanofibers crosslinked directly by hydrogen bonds tends to strongly scatter light, yielding opaque or translucent aerogels [8]. In this work, the surface charges associated with the carboxylate anion preclude the aggregation of the nanofibers by oxidation and the stable aqueous colloidal dispersions is formed at first. Subsequently, the nanofibers are interlinked by hydrogen bonds between the carboxyl groups. In addition, drying the gels in rolls further

preventing the aggregation of nanofibers. Meanwhile, the resultant inter-fiber pores with smaller than 100 nm size and rod-like nanofibers with 4–6 nm width are much smaller than the visible-range light wavelengths. Therefore, the weakened light scattering of aerogels contributes to high transparency. Furthermore, the reflection coefficient at the air-SiCellA interface is about 10 times lower than air-glass interface, as a result, the SiCellA-integrated multi-pane IGU has lessened light loss compared with conventional multi-pane IGU products.

Meanwhile, the mechanical robustness and hydrophobicity of SiCellA are boosted by silanization. The related molecules undergo hydrolysis and chemical condensation reactions with oxidized cellulose nanofibers. The enhanced interaction of the silanized-cellulose chains leads to 200%–300% of increase in tensile and compressive stress than unmodified aerogel, such as high values of tensile stress (270 kPa) and strain (8.8%) (Fig. 1(f)), and ultimate compressive stress is 1.5 MPa. The materials can withstand the loads during manufacturing and service of various window products. Furthermore, the amphiphilic cellulose transforms to hydrophobic with a contact angle of water droplet >150 °C via silanization, making it durable in practical application [6].

To verify the availability of SiCellA in window products, the single-pane window retrofitted with SiCellA is successfully established in winter by Smalyukh et al. (Fig. 1(g)). The infrared image from outside indicates that the retrofitted window has a lower temperature than others, demonstrating the outstanding thermal insulation. In order to compare different types of fenestration in summer and winter, four types of fenestration (SiCellA-IGU, IGU, Retrofit, and Single pane) in two boxes with a high temperature of 40 °C (Fig. 1(h)) and a low temperature of –20 °C (Fig. 1(i)) are developed. In hot box (summer), the temperatures of IGU-based glazing (SiCellA-IGU and IGU) from outside are lower than single-pane glazing (Retrofit and Single pane). Specifically, SiCellA-IGU is colder than IGU and Retrofit is colder than Single pane. On the contrary, the temperature of SiCellA-IGU is the highest in cold box (winter). These results indicate that the multi-pane windows have better performance than single-pane, while SiCellA-retrofitted windows exhibit better performance than conventional windows, proving the great insulating potential of SiCellA in practical windows.

In summary, the SiCellA achieves super-insulating, highly transparent, mechanically robust, and super-hydrophobic. It can be easily fabricated in window-scale for applications. Moreover, low-cost raw materials and strong adhesion of SiCellA to glass enable its extensive utilization in all kinds of window products, as well as skylights. Furthermore, aerogel materials with thermal conductivity even lower than SiCellA are highly desirable. Coincidentally, the scalable anisotropic aerogels with consistent pore alignments by additive freeze-casting offers ultralow thermal conductivity in transverse direction [9], giving the possibility to further enhance the thermal insulation of SiCellA.

The above-mentioned aerogel-insulating glazing can suppress energy loss efficiently by static materials and structures. It should be noted that dynamic window technologies can further harness or hinder energy by switching the structure of materials in response to variable environment, such as thermochromic and electrochromic smart windows [10]. Therefore, it is promising to integrate super-insulating aerogel-glazing with smart window technologies for building energy conservation. For example, attaching structurally variable VO₂ and other supporting layer to

the outside pane can automatically regulate the transmittance of near-infrared (NIR) in response to temperature variation, while inserting SiCellA into the gap between multi-pane can inhibit the energy loss simultaneously. Furthermore, SiCellA-based windows with reconfigurable interwoven structures can further harness radiative cooling in summer and radiative heating in winter by dynamically switching the spectral selectivity of NIR and long-wave infrared (LWIR). For instance, flexible electrochromic design on Pt-modified graphene and Cu-water electrolyte shows a thermal emissivity varied between 0.07 and 0.92 via reversible copper electrodeposition [11]. In the future, the possible combination of optimized SiCellA and smart window technologies will provide a promising route to develop next-generation windows for energy-saving of buildings.

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Declaration of conflicting interests

The authors declare no conflicting interests regarding the content of this article.

Data availability

All data needed to support the conclusions in the paper are presented in the manuscript and/or the Supplementary Materials. Additional data related to this paper may be requested from the corresponding author upon request.

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