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Transparent aerogels reduce energy loss through building windows

Glass panes have been used in windows since the times of ancient Rome, but they exhibit poor thermal insulation. Aerogels made from silanized cellulose nanofibres are better thermal insulators and more transparent than glass, offering an approach to developing window products to reduce the loss of building heating and cooling energy.

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The problem

Commercial and residential buildings consume about 40% of all energy generated globally, most of which is used by heating, ventilation and air conditioning (HVAC) systems[1]. A large fraction of this energy is wasted owing to the poor thermal insulating properties of windows, enabling heat flow between the exterior and interior[1]. Although most windows are double-pane insulating glass units, often with low-emissivity coatings, energy-inefficient single-pane windows are still common[2,3]. To increase the energy efficiency of windows, new insulated window designs and retrofits are needed. Beyond saving energy, thermally insulating glass units and retrofits could also reduce water condensation on windows and improve the comfort of occupants[2]. However, the challenge is developing materials that combine very high optical transparency with a thermal insulation capability comparable to or better than that of still air. Moreover, transparent insulators need to be reliably fabricated at low cost on window-relevant scales.

The solution

We focused on developing visibly transparent, thermally insulating, mechanically stable and flexible aerogel films to serve as transparent thermal barriers. To achieve this unusual combination of physical properties, we designed and fabricated porous nanostructured metamaterials that contain ~99% air by volume[3]. We then developed and applied window products based on these aerogels and performed physical property characterizations and durability tests.

The aerogels are made from cellulose nanofibres, 4–6 nm in diameter, which can be derived from wood or produced by bacteria in a process similar to one used in the food industry[4,5]. The fibres are then crosslinked in a water dispersion to form a hydrogel, before being converted into an aerogel by replacing the fluid medium around the fibres with air through a carefully optimized procedure involving solvent exchange and supercritical drying. The aerogel films can be adhered to plastic substrates and rolled.

To achieve materials with the desired physical properties, particularly a hydrophobic surface, for window applications, we chemically modified the amphiphilic cellulose nanofibres within the aerogel network. The resultant silanized cellulose aerogel (SiCellA) materials were used to laminate a single-pane window and inserted into the gap of a double-pane insulating glass unit (Fig. 1a,b). By assessing the ability of heat to transfer from the hot to cold sides, we demonstrated that the SiCellA materials improve the thermal barrier performance of windows (Fig. 1c–e).

Furthermore, free-standing slabs of SiCellA have a very high visible-range transmissivity of 97–99%, which is higher than that of clear glass (~92%), and, depending on the thickness, typically have a low coefficient of haze. These properties can be linked to the nanoscale morphology: the fibre diameters and pore dimensions are much smaller than the wavelength of visible-range light, which helps to minimize light scattering. Additionally, the SiCellA-based window products exhibit good stability in various tests and SiCellA increased the condensation resistance of the windows.

Overall, we have developed an aerogel that meets various technical targets for applications in building windows and gained broader understanding of how such transparent insulators can be designed and reliably manufactured.

The implications

Increasing the energy efficiency of windows could have environmental and economic benefits. As more than 80% of energy generated globally comes from fossil fuels, making buildings more efficient through new materials and technologies could notably reduce greenhouse gas emissions — the energy lost through windows in the USA alone accounts for 70 million tonnes of CO_2 emissions per year[5]. By consuming less energy to maintain a comfortable indoors environment, the SiCellA-based insulating glass units and retrofits could help avoid greenhouse gas emissions associated with energy generation and decrease building maintenance costs for homeowners and businesses.

Nevertheless, further research is needed to reduce the haze of thick aerogel slabs and to lower manufacturing costs to drive widespread deployment of SiCellA-based window products. In particular, alternatives to CO_2-based supercritical drying of aerogels on plastic supports in rolls might reduce manufacturing costs. Porous mesostructured materials with a thermal conductivity even lower than that of SiCellA are highly desirable and can be designed using insight from our current study. We are now aiming to make such pre-designed transparent insulators, including on window-relevant scales.

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EXPERT OPINION

"The material that is presented is original, addresses a topic of high societal relevance and represents a notable contribution to the state of the art. In my opinion, the proposed aerogel represents a breakthrough in the field, with the potential to have a disruptive impact on the design and retrofit of high-performance buildings. I especially appreciate the attention to scale-up potential and the exploration of different applications." **Roel Loonen, Eindhoven University of Technology, Eindhoven, the Netherlands.**

FIGURE

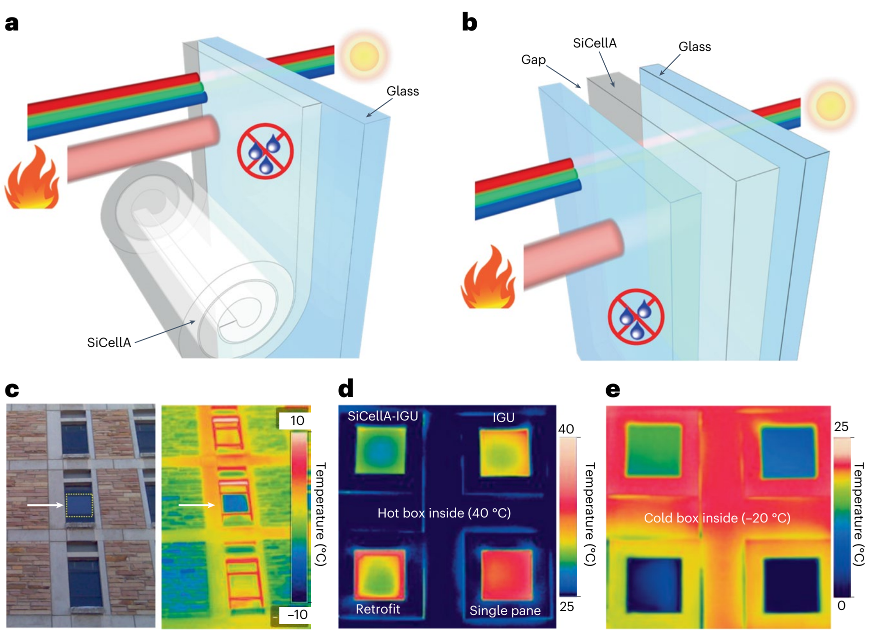

Fig. 1 | SiCellA-based window products. a,**b**, Schematics of a window retrofitted with a SiCellA film (**a**) and an insulating glass unit (IGU) with a SiCellA slab inserted between the glass panes (**b**). SiCellA increases the thermal insulation and condensation resistance of the windows while maintaining high, haze-free visible-range optical transparency. **c**, Thermal imaging of a single-pane window retrofitted with a 1.5-mm-thick SiCellA film (indicated by the arrow). The retrofitted window is colder than similar windows without the SiCellA film as it is more efficient at blocking heat flow. **d**,**e**, Infrared thermal imaging photos of different fenestrations mounted in the openings of hot (**d**) and cold (**e**) boxes with inside temperatures of 40 °C and −20 °C, mimicking interior–exterior heat exchange during summer and winter, respectively. 'SiCellA-IGU' and 'IGU' are double-pane IGUs with and without a SiCellA film, respectively; 'retrofit' is single-pane glass retrofitted with a SiCellA film, whereas 'single pane' is without.

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BEHIND THE PAPER

Fall 2014 was the beginning of my first sabbatical, offering the opportunity to travel and collaborate internationally. However, my son was about 1 year old, so I preferred to do my sabbatical at NREL, a 30 min drive from Boulder. At the time, I was excited about challenging 'pure physics' problems, especially ones related to knot solitons. However, I was shocked when I learned that 20% of building energy is lost through windows and decided to do something about it. Fortunately, the 'stars aligned': the Renewable and Sustainable Energy Institute got a new laboratory building, enabling me to secure lab space, and ARPA-E announced the 'SHIELD' programme to address the window problem, and my proposal was funded. Since 2016, my group has had an applied physics branch and pursues solutions to the 'knotty problem' of window energy efficiency to slow the growing energy demand. This study describes an approach towards this goal, but more will follow. **I.I.S.**

FROM THE EDITOR

"This work by Abraham et al. stood out to me because it provides windows with thermal insulation while maintaining high transparency and low haze, something that has proved challenging so far. The aerogel can be implemented in both existing and new windows, representing a viable solution to improve the energy efficiency of the building envelope." **Giulia Tregnago, Senior Editor, *Nature Energy*.**