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Radiative electrochromism for energy-efficient buildings

An aqueous electrochromic device has been developed that enables reversible tuning of its thermal emissivity with minimal electrical power input. The device allows for all-season radiative thermoregulation, leading towards year-round energy savings for buildings.

The mission

The operation of buildings accounts for 30% of global energy consumption and 27% of total energy sector greenhouse gas emissions[1], to which indoor heating and cooling is a major contributor. Smart building envelopes that enable occupants to dynamically modulate the thermal emissivity of a building in response to seasonal or diurnal variations in the conditions could greatly increase the energy efficiency. For example, electrochromic windows, which change colour upon application of an electrical stimulus, can enable dynamic control of the solar heat gain. However, these devices typically operate in the visible and near-infrared (IR) wavelength regimes only, suffer from poor long-term durability and use flammable electrolytes, limiting their scalability. Radiative thermoregulation based on dynamic tuning of the mid-IR thermal emissivity to modulate the radiative heat transfer is a promising approach to further enhance the energy efficiency, as demonstrated by thermochromic devices[2,3] that undergo a temperature-driven metal-to-insulator phase transition. Reversible metal electrodeposition[4] can also lead to a drastic change in the mid-IR optical properties of a device and, compared with thermochromic devices with a fixed phase-change temperature, offers greater on-demand tunability. Yet, to develop a scalable and durable electrochromic building envelope for radiative thermal management requires redesign of the electrochemical reaction at the electrolyte–electrode interface and device engineering to enable operation at mid-IR wavelengths with on-demand tunability over a wide thermal emissivity range.

The solution

To address this issue, we developed a mid-IR electrochromic device that combines a non-flammable aqueous electrolyte, reversible Cu electrodeposition and an ultra-wideband transparent conductive electrode based on Pt-modified monolayer graphene[5] (Fig. 1a). The Pt-modified transparent conductive electrode is optimized to exhibit low mid-IR reflectivity and, together with the IR-absorbing aqueous electrolyte, endows the pristine device with high thermal emissivity. Application of a negative bias to the transparent electrode leads to deposition of a thin Cu film on the transparent electrode, which lowers the emissivity and suppresses radiative heat exchange. Reversing the bias to positive dissolves the Cu film and switches the device from the heating state back to the high-emissivity, cooling state. The reversibility and range over which the emissivity can be tuned strongly depend on the surface modification of graphene and the electrolyte composition.

With Pt-modified graphene and the optimized electrolyte composition, the electrochromic device realizes a mid-IR thermal emissivity contrast of 0.85 with reasonable tunability retention after 2,500 cycles. Density functional theory simulations show that Pt has high affinity for the deposited Cu atoms, resulting in both uniform electrodeposition and a low overpotential. On a system level, building energy simulations show that up to 43.1 MBtu of averaged HVAC (heating, ventilation and air-conditioning) energy could be saved by applying the electrochromic device as a dynamic building envelope (Fig. 1b). The reversible electrodeposition is non-volatile and efficient; thus, the energy consumption for switching is negligible compared with the building's existing electricity usage.

Future directions

Our mid-IR electrochromic device and its visible and near-IR counterparts[4] offer a platform for dynamically tunable light and heat management. On the application side, it will be useful to perform a life cycle assessment and techno-economic analysis to quantitively determine the optimal application scenario based on various parameters, such as building type and climate zone. The opto-electrochemical design also shows how advances in photonics and electrochemistry can be applied in thermal and building engineering.

One limitation of our electrochromic device is the cost. Some of the materials used are expensive and complicated to fabricate, such as monolayer graphene. Therefore, research efforts to improve manufacturing scalability or to find alternatives are essential. Moreover, after addressing the mid-IR tunability, modulation of solar radiation should be incorporated to achieve daytime sub-ambient radiative cooling[6], which will be increasingly important as the global temperature increases.

Moving forward will require more in-depth characterization and theoretical insight to understand the side reactions and how they influence the optical properties of the device and the reversibility of the metal electrodeposition, which might enable us to enhance the performance and broaden the choice of materials. The electrochemical principles common to electrochromism and electrochemical energy storage and conversion could also lead to cross-displinary approaches to technologies for sustainable energy systems.

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EXPERT OPINION

"Electrochromic devices rarely tune in the mid-IR. Now, using transparent conductive graphene as the electrode and a Cu–water solution as the electrolyte, this study reports record-high mid-IR thermal emissivity contrast. This research has revealed a conceptual advance towards durable and safe electrochromic devices, and demonstrated the feasibility of applying such devices in a building envelope." **Yi Long, Chinese University of Hong Kong, Hong Kong, PRC.**

FIGURE

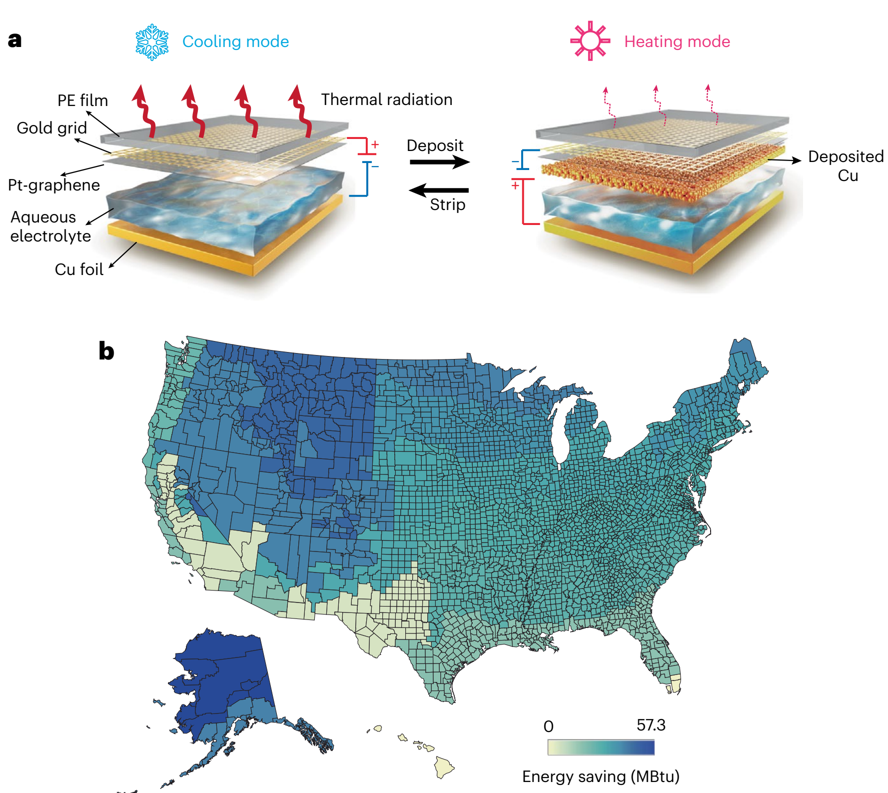

Fig. 1 | Dynamic electrochromism can increase the energy efficiency of buildings. a, Schematic of our electrochromic device based on reversible Cu electrodeposition. The device can be switched between radiative cooling and heating modes by altering the applied bias to dissolve or deposit Cu on the Pt-modified graphene electrode. **b**, Map showing the calculated energy savings of applying the electrochromic device as a dynamic building envelope across the USA. PE, polyethylene. © 2023, Sui, C. et al.

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BEHIND THE PAPER

Electrochemical dynamic light and heat management has been a major theme in my research group. Standing at the intersection of electrochemistry, photonics, materials science and heat transfer, we see immense opportunities to be part of the joint academic force to fight against climate change. Largely motivated by the recent progress in daytime radiative cooling and personal thermal management, we chose to tackle mid-IR and multispectral tuning. Like any sustainability problem, it takes several studies (and many more unpublished failed attempts) to find potential solutions that achieve the right balance between disruptiveness and scalability. Reversible metal electrodeposition is particularly intriguing owing to its wide tunability and the considerable research effort being invested in batteries and electrocatalysis. We look forward to more cross-disciplinary and synergistic developments by adding photon management into the portfolio of electrification-enabled technologies. **P.-C.H.**

FROM THE EDITOR

"The energy consumption of buildings has reached an extent to which without improvements in their sustainability, an energy-efficient and carbon-neutral future is no longer possible. The electrochromic window design here serves to exert intelligent control of the radiative properties so that the thermal energy is either released or absorbed. The remarkable energy saving capacity demonstrated does suggest a pathway towards greener buildings." **Yaoqing Zhang, Senior Editor, *Nature Sustainability*.**