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COMMENTARY

Smart windows with reversible metal alloys: Toward net-zero energy buildings

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In the current social context that advocates low-carbon energy conservation, the manipulation of light flow and heat flow holds significant social and economic value.[1,2] With the increasing demand for building energy and massive carbon dioxide emissions, technologies that can dynamically regulate solar radiation and thermal radiation are crucial for achieving net-zero energy buildings. Electrochromic technologies have therefore developed rapidly, giving rise to smart windows, coatings, and roofs for intelligent thermal management under different climatic and environmental conditions.[1-3]

Electrochromic devices rely on ion intercalation/deintercalation or redox reactions under applied voltage, allowing higher degrees of freedom. By tuning applied bias, electrochromic windows can reversibly switch optical states and regulate solar transmission to match building demands under variable lighting conditions. Yet, narrow modulation range, slow response, and non-neutral coloration remain major barriers to large-scale commercialization. Thus, electrically driven devices that enable simultaneous regulation of light and heat hold significant promise for improving building energy efficiency.

Against this background, Wang et al. recently developed a high-performance dynamic photothermal regulation device based on reversible CuNi alloy electrodeposition, designed through electrolyte interface engineering.[4] A key innovation of their work lies in the introduction of competitive Gd^{3+} ion additives. By compressing the diffusion layer and leveraging the electrostatic shielding effect, dendritic growth is suppressed and smooth, dense metallic films are achieved. This interface-engineered deposition not only enhances cycling stability but also delivers outstanding optical modulation: ultra-low visible transmittance (<0.001% at 550 nm), high near-infrared reflectance, and rapid switching. In the transparent state, the device allows solar radiation to pass through, facilitating indoor heating. Under applied bias, Cu^{2+} and Ni^{2+} co-deposit to form a CuNi alloy layer, which effectively blocks sunlight and lowers the thermal load of the building.

Another highlight of this work is its demonstration of functional versatility and scalability. By homogenizing the electric field and reducing ion polarization differences, Wang et al. designed dot-matrix adjustable devices and scaled-up modules. These enable independent zoning control, gesture recognition integration, and programmable multi-level states, thus opening possibilities for intelligent façade systems. However, the Cu–Ni device exhibits a slightly yellowish hue in its transparent state, which could limit its suitability for window applications. Future studies may explore alternative alloy systems, such as Cu–Bi reversible electrodeposition,[2] to achieve color-neutral transparency while preserving large optical modulation. Large-area demonstrations and EnergyPlus simulations further revealed superior energy-saving potential compared with commercial electrochromic devices, with global deployment projected to save up to 45.5 MJ/m^2 annually and achieve a maximum energy-saving ratio (the percentage reduction in total HVAC energy demand relative to a static glazing baseline) of 56.6%. Such results underscore the real-world promise of reversible metal electrodeposition (RMED) technologies, moving beyond laboratory-scale demonstrations.

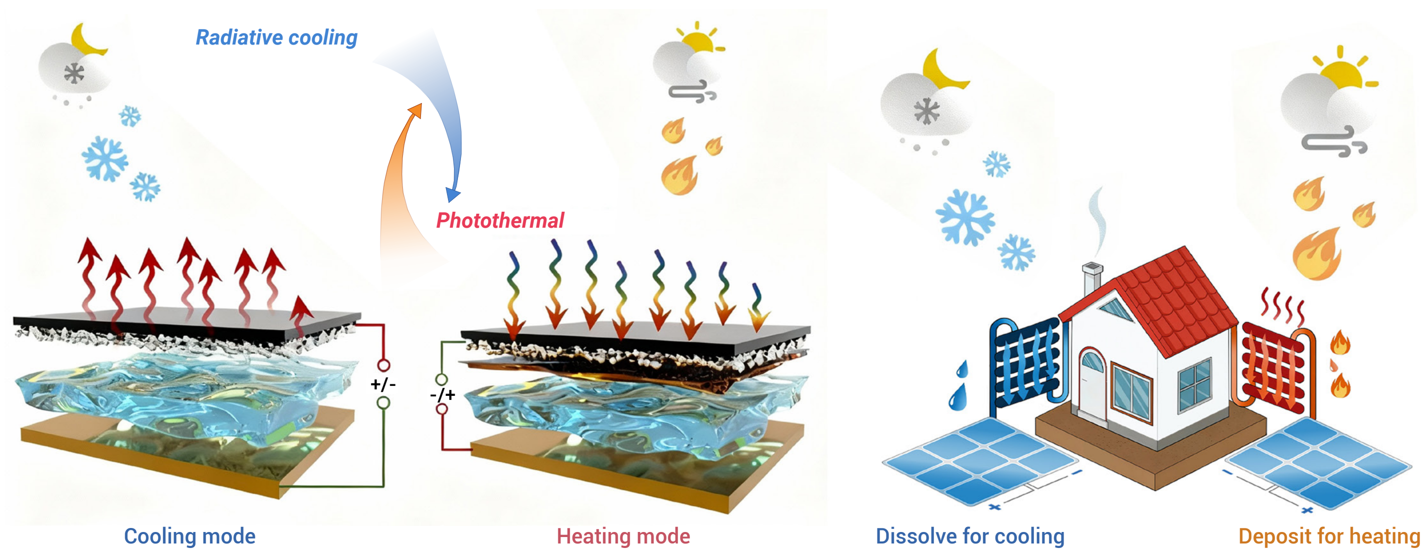

Figure 1. Dynamic regulation of solar and thermal radiation enabled by reversible metal electrodeposition.[5] Copyright 2025, ACS

Beyond solar radiation control, Wang et al. innovatively extended RMED to thermal infrared management by integrating photonic thin-film electrodes.[5] This hybrid design tackles a long-standing challenge in building energy regulation: the cross-spectral conflicts between solar harvesting and radiative cooling. In their device, voltage-controlled Cu deposition renders the electrode low-emissivity, while the photonic structure provides high solar absorption via resonance and field localization, thus enabling photothermal conversion during the daytime. At night, Cu dissolution restores high emissivity, allowing thermal radiation through the atmospheric transparency windows, thereby achieving passive radiative cooling (Figure 1). This dual-functionality device bridges solar modulation and thermal emission control, offering a novel route to all-day energy regulation.

The implications of these innovations extend beyond single-device performance. By integrating RMED-based smart windows with building water circulation systems, heat harvested in daytime can be stored and cold energy from nighttime cooling can be retained, providing active thermal buffering for buildings. Moreover, the demonstrated durability against abrasion, flame, and UV exposure suggests pathways toward practical implementation under harsh environmental conditions. Together, these advances establish RMED as a promising multifunctional platform for both photothermal conversion and radiative cooling, with potential applications not only in smart buildings but also in thermal management of energy systems.

Despite these breakthroughs, practical deployment faces challenges in three major aspects. First, scaling to larger areas introduces potential gradients between central and edge regions, which compromises uniform metal deposition and weakens overall optical modulation. Similar potential-drop behavior and its mitigation strategies have been quantitatively analyzed using equivalent circuit models in prior RMED studies.[2] Rational electrode structures and electrolyte management strategies will be required to ensure consistent performance. Second, environmental durability under real-world conditions remains a critical hurdle. Building envelopes experience continuous stress from weather fluctuations, UV exposure, and mechanical load, and device performance must be maintained under such conditions. Third, the electrochemical cycle life of current devices remains insufficient compared to the decades-long service requirements of architectural applications. Previous studies have demonstrated that improving electrolyte formulations by polymer inhibitor and interfacial uniformity can greatly extend RMED device stability, as shown in large-area systems achieving thousands of reversible cycles.[2] Future improvements in electrode and electrolyte design, interface stability, and encapsulation strategies will be essential to extend operational lifetime. A fourth important challenge is resting stability—the ability of RMED devices to maintain their optical state without external power. In Cu-based systems, slow spontaneous metal dissolution can occur during open-circuit conditions, leading to gradual performance degradation. Developing stable electrolyte compositions and encapsulation designs will be essential to overcome this issue.

In conclusion, the research conducted by Wang and colleagues demonstrates reversible metal electrodeposition as a versatile and powerful platform for photothermal regulation. Through electrolyte interface engineering, scalable architectures, and hybrid photonic-electrode integration, their work expands the functionality of RMED devices from solar control to dual-band regulation, encompassing both daytime photothermal conversion and nighttime radiative cooling. This study represents a significant step toward achieving energy-efficient, adaptive, and sustainable building environments. Future research should focus on scale-up, durability, and lifetime extension, thereby accelerating the transition of RMED-based devices from laboratory prototypes to real-world building applications.

REFERENCES

1. Sui C., Pu, J. Chen T. H., et al. (2023). Dynamic electrochromism for all-season r adiative thermoregulation. *Nat. Sustain.* **6**:428–437. DOI:10.1038/s41893-022-01023-2
2. Strand M.T. Hernandez T.S., Danner M.G., et al. (2021). Polymer inhibitors enable >900 cm^2 dynamic windows based on reversible metal electrodeposition with high solar modulation. *Nat. Energy* **6**:546–554. DOI:10.1038/s41560-021-00816-7
3. Imamura A., Kimura M., Kon T. et al. (2009). Bi-based electrochromic cell with mediator for white/black imaging. *Sol. Energ. Mat. Sol. C.* **93**:2079–2082. DOI:10.1016/j.solmat.2009.05.001
4. Wang W., Wang L., Liu G., et al. (2025). Competitive ion driven reversible Cu and Ni electrodeposition for smart windows with synergistic optical and thermal regulation. *Chem. Eng. J.* **521**:166647. DOI:10.1016/j.cej.2025.166647
5. Wang W., Wang L., Jin S., et al. (2025). Electrochromic harvester for all-day energy savings in buildings. *ACS Energy Lett.* **10**:3231–3240. DOI:10.1021/acsenergylett.5c01153

DECLARATION OF INTERESTS

The author declares no competing interests.