Spatiotemporal diffusion metamaterials: Theories and applications

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Ⅰ Background of the Perspective

Spatiotemporal diffusion metamaterials have emerged as a groundbreaking innovation with the potential to revolutionize the control of energy and mass transfer. Unlike traditional static structures, these dynamic metamaterials incorporate a temporal dimension, allowing for the modulation of diffusion processes in real-time.

This perspective explores the fundamental theories and practical applications of spatiotemporal diffusion metamaterials, emphasizing their ability to achieve nonreciprocal, topological, and tunable properties.

Ⅱ Main Theories

Spatiotemporal transformation theory

Spatiotemporal transformation theory extends traditional transformation theory by dynamically modulating material parameters like thermal conductivity in both spatial and temporal dimensions. This allows a single structure to adapt to changing conditions, enhancing functionalities like thermal coding and nonreciprocal transport.

Wavelike diffusion theory

Wavelike diffusion theory involves the modulation of diffusion fields with periodic spatiotemporal distributions. This results in unique properties such as nonreciprocal transport, achieved through mechanisms like effective advection and thermal Willis coupling, offering advanced control over heat and mass diffusion processes

Ⅲ Structures and Applications

Practical Structures

Active structures, such as rotating disks and slide rheostats, achieve spatiotemporal modulation by creating spatial variations. Field-dependent materials like strontium titanate adapt thermal conductivity in response to environmental changes.

Distinct Applications

Nonreciprocal heat, energy and mass transfer, as effective advection and Willis coupling.
Dynamic multiphysics signal regulation by the magneto-thermoelectric effect.
Intelligent thermal management with adaptive structures for real-time heat regulation.

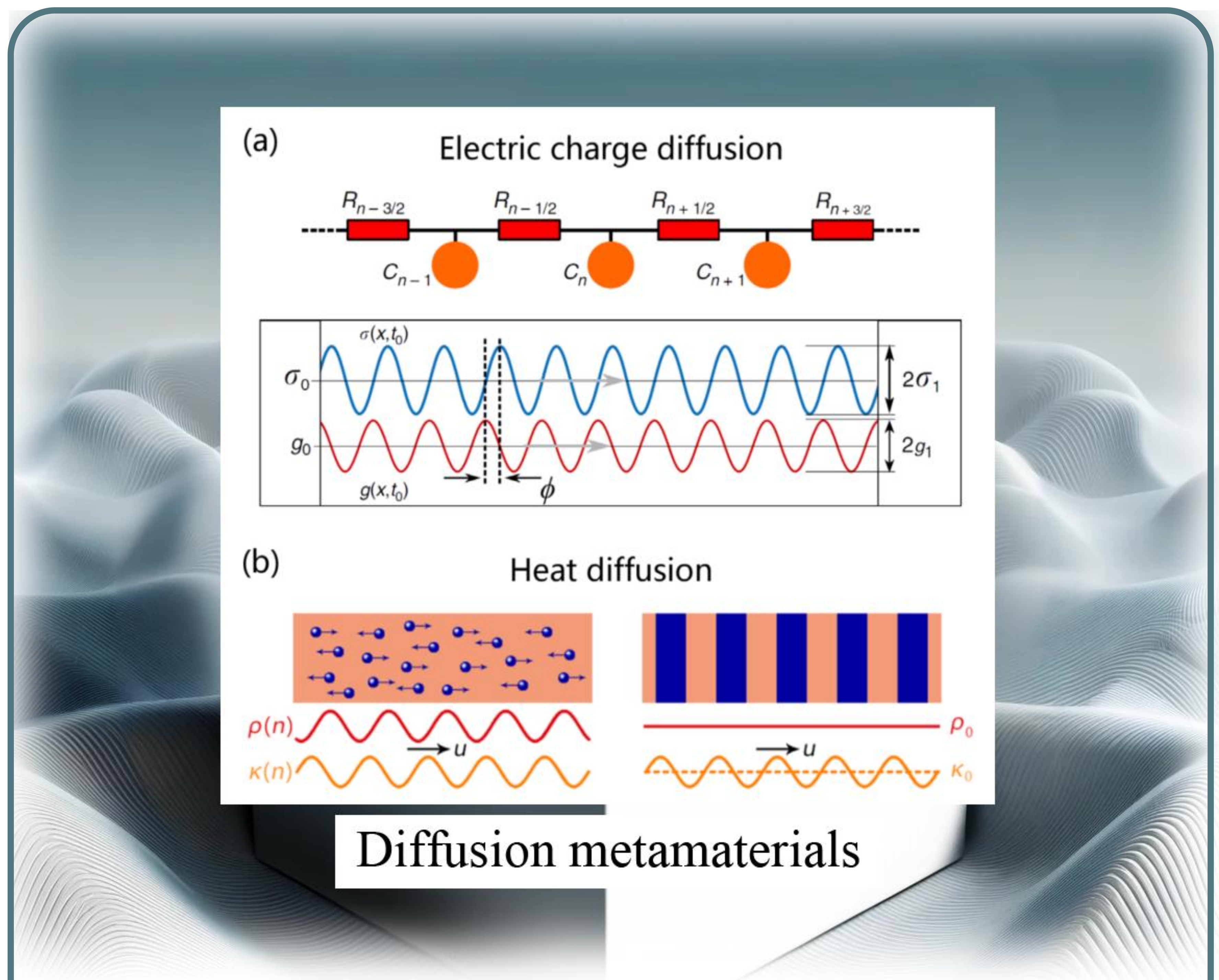

FIG. 1. Concept of spatiotemporal modulation in diffusion system. (a) Electric charge diffusion with spatiotemporal electric conductivity r and capacity g. Adapted from Nat. Commun. 11, 3733 (2020). (b) Heat diffusion with spatiotemporal mass density q and thermal conductivity j. Adapted from Phys. Rev. Lett. 129, 155901 (2022)

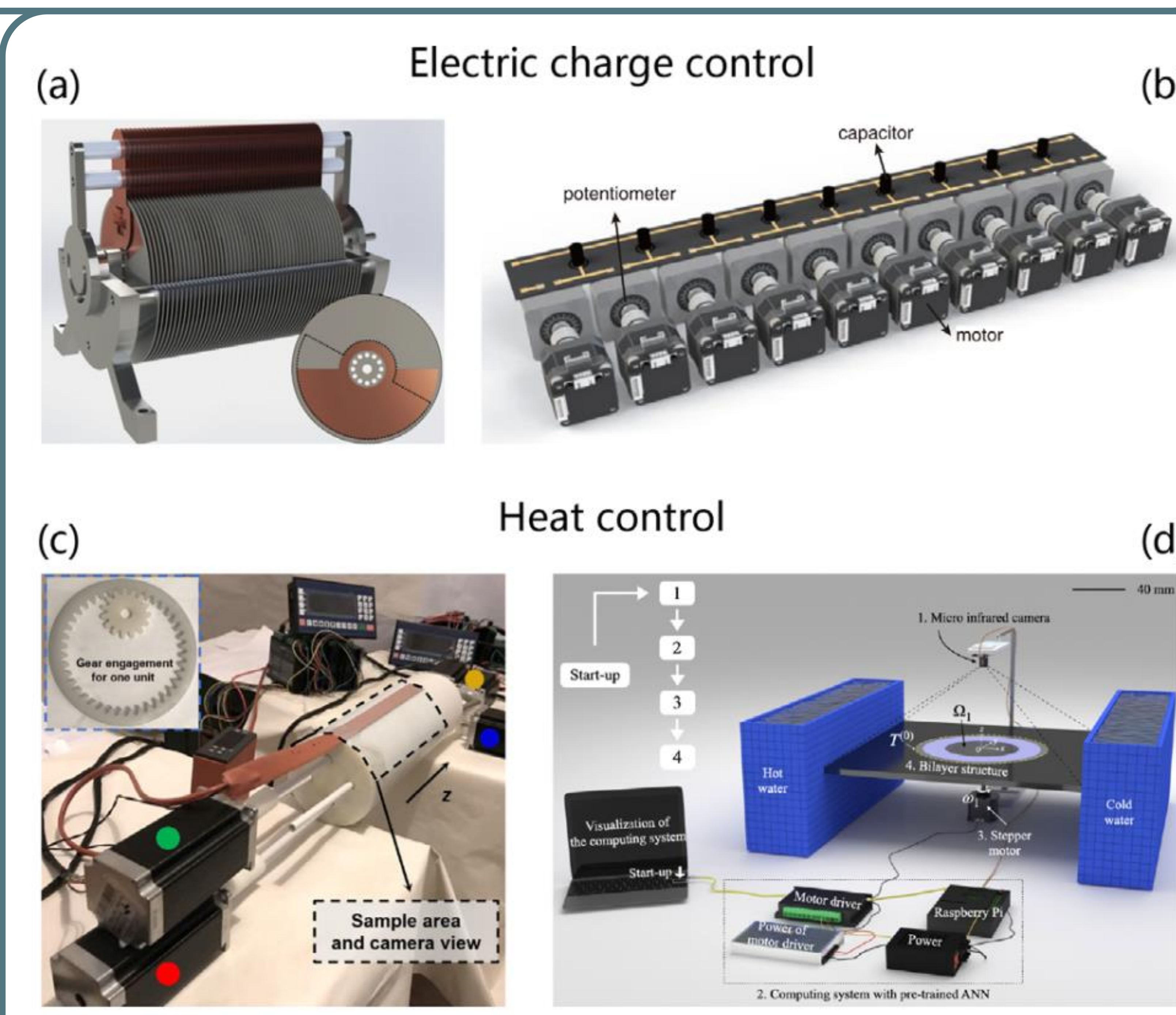

FIG. 2. Practical ways of spatiotemporal modulation. (a) Rotating disks with spatiotemporal capacitors and resistors. Adapted from Nat. Commun. 11, 3733 (2020). (b) Equivalent circuit with spatiotemporal electric conductivity. Adapted from Phys. Rev. Lett. 129, 256601 (2022). (c) Spatiotemporal convection-assisted thermal diffusion. Adapted from Nat. Phys. 18, 450 (2022). (d) Deep learning-assisted heat control. Adapted from Adv. Mater. 36, 2305791 (2024).

Reference
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