Manipulating metals for adaptive thermal camouflage

Mingyang Li, Dongqing Liu*, Haifeng Cheng, Liang Peng, Mei Zu

Many species in nature have evolved remarkable strategies to visually adapt to the surroundings for the purpose of protection and predation. Similarly, acquiring the capabilities of adaptively camouflaging in the infrared (IR) spectrum has emerged as an intriguing but highly challenging technology in recent years. Here, we report adaptive thermal camouflage devices by bridging the optical and radiative properties of nanoscopic platinum (Pt) films and silver (Ag) electrodeposited Pt films. Specifically, these metal-based devices have large, uniform, and consistent IR tunabilities in mid-wave IR (MWIR) and long-wave IR (LWIR) atmospheric transmission windows (ATWs). Furthermore, these devices can be easily multiplexed, enlarged, applied to rough and flexible substrates, or colored, demonstrating their multiple adaptive camouflaging capabilities. We believe that this technology will be advantageous not only in various adaptive camouflage platforms but also in many thermal radiation management-related technologies.

INTRODUCTION

Dynamically controlling the infrared (IR) features of objects such as human body and military equipment for the purpose of camouflage in the IR spectrum has attracted extensive research interests in recent years (1–4). To achieve this goal, the radiant heat emitted from an object should be precisely controlled to match the background. According to the Stefan-Boltzmann law, the radiant heat of the object is proportional to both the fourth power of its absolute temperature and the emittance of the surface. Thus, dynamic control of the temperature or thermal emittance of the object offers two possible approaches to attain adaptive thermal camouflage. For dynamic control of the temperature, microfluidic networks (5) and thermoelectric systems (6, 7) have been proposed. Although remarkable temperature regulations have been reached by them, the former necessitates complex heating, cooling, and pneumatic systems whereas the latter encounters high energy consumption and serious heat accumulation problems. Instead, dynamic control of the thermal emittance is a more feasible and energy-efficient way to meet the camouflage purpose. For example, the radiant heat of the object can be dynamically controlled without changing its real temperature by attaching a film with tunable IR emittances. On the basis of this approach, various inspiring IR modulation systems have been developed. However, problems still remained: Phase-change materials are restricted by the relatively fixed working temperatures (4, 8); IR electrochromic devices usually suffer from comparatively low IR emittance tunabilities (∆ε) and narrow IR modulation ranges (9–11); cephalopod-inspired systems are subject to inadequate total–Δε and narrow IR modulation ranges (9–11); and cephalopod-inspired systems are subject to inadequate total IR emittance changes and high triggering voltage (1); graphene-based modulators lack low-cost manufacturing techniques and visible compatibility (2, 12–14). Therefore, developing new adaptive materials and systems that simultaneously avoid the drawbacks is highly anticipated.

Metals are prominent for ultrahigh reflectance (~100%) over the entire IR spectrum in their bulk states (15, 16), which makes them the perfect IR reflectors to suppress thermal radiation. In contrast, by reducing the dimensions of metals to nanometer or even sub-nanometer scales, new phenomena such as hybridized localized surface plasmon resonance (17, 18) and free electron–induced high losses appear (19, 20), which can lead to high absorption (21) or partial transmission (19) over the visible-IR wavelengths. Furthermore, because the IR absorption and IR transmission of nanoscopic metals can be converted to IR reflection by eliminating their nanostructures or increasing their scales, manipulating their scales and structures may bring unexpected IR modulation capabilities. Moreover, by forming microscale rough surface structures (1) or performing on flexible IR-transparent substrates (15), metals can demonstrate diffuse-dominated IR reflection mode or flexible IR applications. Thus, manipulating metals may provide promising approaches to solve the multiple optical and radiative challenges in adaptive thermal camouflage. Besides, owing to the high reflectance in the visible spectrum, metals can be easily colored by incorporating thin dielectric optical coatings (22–24), providing possible visible coloring strategies without substantially affecting their IR properties. However, despite these advantages, systems that can fully use the properties of metals to attain dynamic IR modulation have not yet appeared. For instance, reversible metal electrodeposition systems (25–28), liquid-metal–based transformations (29, 30), electro tunable nanoplasmonic liquid mirror (31), and cephalopod-inspired systems (1, 32) provide impressive methods to manipulate metals, but most of them have no or limited IR responses mainly due to their IR opaque electrodes, substrates, or surrounding media. Therefore, exploring ways to effectively exploit the unique advantages of metals is the key to revealing their potentials in adaptive thermal camouflage.

Inspired by the multiple optical and radiative properties of metals, we report nanoscopic platinum (Pt) film–based reversible silver (Ag) electrodeposition (RSE) devices that exhibit excellent adaptive thermal camouflage capabilities (Fig. 1A). Primarily, because the nanoscopic Pt films have high IR absorption and partial IR transmission and their IR transmission part can be transformed to IR absorption by the IR-absorbing gel electrolyte layer, the devices exhibit high-emittance states when no metals have been electrodeposited. After the deposition voltage has been applied, Ag will be gradually electrodeposited on the nanoscopic Pt film surfaces and gradually convert the IR absorption and IR transmission of the nanoscopic Pt films to IR reflection by forming Ag electrodeposited Pt films, thereby enabling the devices to achieve low-emittance
states. Moreover, because the nanoscopic Pt film cannot be dissolved and the Ag can be deposited and dissolved for multiple times, these devices are capable of switching between high- and low-emittance states for many cycles. Specifically, the resulting devices have large, uniform, and consistent IR tunabilities in both mid-wave IR (MWIR; 3 to 5 μm) and long-wave IR (LWIR; 7.5 to 13 μm) atmospheric transmission windows (ATWs) \( \Delta \varepsilon_{MWIR} \approx 0.77; \Delta \varepsilon_{LWIR} \approx 0.71 \). Moreover, by patterning the nanoscopic Pt films, adding conductive grids, using rough and flexible substrates, or incorporating structural color coatings, the devices can be easily multiplexed, enlarged, applied to rough and flexible substrates, or colored, largely expanding their camouflaging scenarios. Most of their performance is comparable to or exceeds those IR modulation systems in previous reports (table S1).

**RESULTS**

**IR modulation potentials**

To explore the IR modulation potential of our metal-based devices, we first investigated the electrical properties of the nanoscopic Pt...
films, which were directly evaporated on the polished BaF₂ substrates by an electron-beam evaporation system. When the Pt thickness was increased from 1 to 20 nm, the sheet resistance was nonlinearly decreased from ~12 kilohm square⁻¹ to ~18.9 ohm square⁻¹ (Fig. 1B), which is a typical electrical percolation process during ultrathin metal film deposition. Apart from this, the electrodeposition threshold of the nanoscopic Pt films was also studied. As shown in the inset of Fig. 1B, Ag was successfully electrodeposited on the 2-nm Pt film in the RSE three-electrode system (blocked the light-reflecting Pt plate counter electrode behind it), proving that 2 nm is their threshold to achieve electrodeposition.

Next, we examined the spectral responses of the nanoscopic Pt films. As illustrated in fig. S1, when the Pt thickness was increased from 0 to 11 nm, the Pt films showed huge decreases in IR transmittance, whereas their IR reflectance only experienced very limited increases, which indicates that IR absorption dominated their spectral responses. The strong and broadband IR absorption is caused by two grounds. On the one hand, the Volmer-Weber growth of the evaporated Pt films on heterogeneous surfaces naturally leads to physically connected Pt clusters with nanoscopic sizes and shapes in their percolated stages (Fig. 1C), allowing them to absorb light in the IR wavelengths by the increased scattering of free electrons at the boundaries (fig. S2A). On the other hand, apart from serving as the host scaffold, the IR-transparent BaF₂ substrate with relatively low refractive index (n ≈ 1.4) exhibits antireflective properties (~4.7 to ~15% average reflectance reduction in the range of 3 to 14 μm) due to refractive index matching (Fig. 1D), further enhancing the IR absorption of the nanoscopic Pt films (fig. S2, B to H). Then, we calculated the ratio of average IR transmittance (T%), average IR reflectance (R%), average Pt-induced IR absorbance (PA%), and average substrate-induced IR absorbance (SA%) of the Pt evaporated BaF₂ substrates (Pt/BaF₂ substrates) in the range of 3 to 14 μm (Fig. 1E). Because only the Pt-induced IR absorption and the IR transmission parts of the Pt/BaF₂ substrates have the potential to be converted to IR reflection by the electrodeposited Ag films, their potential IR modulation ranges can be estimated by summing up the Pt-induced IR absorption and the IR transmission parts. Therefore, the potential IR modulation range of the Pt/BaF₂ substrates can reach ~84.8% (2 nm), ~80.7% (3 nm), ~77.1% (4 nm), and ~65.9% (5 nm) of their total spectral responses, respectively.

Then, we measured the potential IR modulation ranges and cycling stability of the nanoscopic Pt films in the three-electrode RSE system. The Pt/BaF₂ substrate with Pt thickness of 3 nm was used as a representative. As illustrated in Fig. 1F, after electrodepositing at ~2.2 V for 15 s, the average IR reflectance (3 to 14 μm) of the 3 nm Pt/BaF₂ substrate was increased from ~8.4 to ~83.1%, very close to the highest possible reflectance (represented by a BaF₂ substrate covered standard gold film) when 100% of its Pt-induced IR absorption and IR transmission has been converted to IR reflection. To further explain such high IR reflectance increment, we compared the morphologies of electrodeposited Ag film on the 3-nm Pt film with that on an indium tin oxide (ITO) electrode (~14 ohm square⁻¹). Because of the energy favorable interface between Ag and Pt (27, 33–35), the electrodeposited Ag film showed much more uniform, coherent, and fine-grained morphologies on the 3-nm Pt film (Fig. 1G and fig. S3), which is the reason why the nanoscopic Pt film can be converted to a high IR reflective film within a short time. Meanwhile, the cycling stability of the 3-nm Pt film was also examined in the three-electrode system. The nearly identical potentiostatic cycling curves confirm that stable and reversible electrodeposition can be performed by the nanoscopic Pt films (fig. S4).

Last, we inspected whether the IR transmission part of the nanoscopic Pt films can be effectively used for IR modulation after the device assembly. Because the assembled devices rely on converting IR absorption to IR reflection to provide emittance changes, if the IR transmission part of their nanoscopic Pt films cannot be effectively absorbed, their IR modulation ranges will be substantially reduced. As illustrated in fig. S5, because of the strong IR absorption of the gel electrolyte, the assembled devices show no IR transmission and their IR reflectance are very close to the unassembled Pt/BaF₂ substrates. For opaque entities like the assembled devices, the sum of absorbance and reflectance equals to unity; therefore, we can conclude that nearly all the IR transmission part of the Pt/BaF₂ substrates has been transformed to IR absorption, enabling the devices to fully exploit their IR modulation potentials.

Dynamic IR performance

To evaluate the dynamic IR performance of the assembled devices with Pt thickness from 2 to 5 nm (denoted as device-2, device-3, device-4, and device-5, respectively), we attached them on a 50°C hot plate to record their real-time MWIR and LWIR images (Fig. 2, A and B; fig. S6; and movie S1). When applying a negative voltage of 2.2 V, Ag films were gradually electrodeposited on the Pt surfaces and the apparent temperature (displayed by the IR cameras) of these devices gradually decreased. After electrodeposition for 10 s, they underwent large apparent temperature changes (central region of ~19.8°C and ~21.1°C (device-2), ~19.2°C and ~20.7°C (device-3), ~15.9°C and ~18.0°C (device-4), and ~16.3°C and 15.3°C (device-5) in the MWIR and LWIR images, respectively (Fig. 2, C and D, and fig. S6). When applying a positive voltage of 0.8 V for 14 s, the electrodeposited Ag film was completely dissolved into the electrolyte and they all returned to their initial states, indicating the reversibility of these devices (fig. S7). The color distribution of these devices in the MWIR and LWIR images during the electrodeposition process (Fig. 2, A and B, and fig. S6) shows when the Pt thickness reaches 3 nm, high IR modulation uniformity can be obtained on ~5-cm² scale. This is also evidenced by their apparent temperature difference between the central and peripheral regions (ΔT_center-Periphery) in the LWIR images (Fig. 2E). The sheet resistance of the nanoscopic Pt films (such as ~253 ohm square⁻¹ for device-3 and 162 ohm square⁻¹ for device-4) is relatively high compared to the ITO electrodes in conventional electrodeposition systems, but the energy favorable interfaces between the electrodeposited Ag and Pt films facilitate the uniform Ag deposition and eventually lead to uniform IR modulation.

The nearly identical apparent temperature changes of these devices in the MWIR and LWIR images (fig. S6, C to J) suggest that high IR modulation consistency can be achieved over the MWIR and LWIR ATWs. Moreover, because the coherent interfaces between the nanoscopic Pt films and the electrodeposited Ag films form effective conductive channels for galvanic protection and the viscous gel electrolyte slows the corrosive anions from diffusing into the Ag films (36), the intermediate states of device-3 remain nearly unchanged over 20 min by applying a small protective current of ~4 μA/cm² (fig. S8). Owing to the intermediate state stability, the “real-time” total IR reflectance spectra of device-3 could be easily measured by applying a protective current after the electrodeposition stages (Fig. 2F). Similarly, we measured the “real-time” total IR...
reflectance spectra of device-4 and device-5 (fig. S9). By integrating the spectral data of these devices, we calculated their maximum emittance tunability ranges in the MWIR and LWIR ATWs (Fig. 2G). Particularly, device-3, with $\Delta \varepsilon_{\text{MWIR}}$ of 0.77 and $\Delta \varepsilon_{\text{LWIR}}$ of 0.71, exhibits almost the largest MWIR and LWIR modulation ranges among previously reported IR modulation systems (table S1).

The cycling stability of device-3 was measured by the potentiostatic cycling test. The real-time LWIR images (fig. S10) and the corresponding apparent temperature curves at the central and peripheral regions of device-3 (Fig. 2H) show that they can steadily operate up to 350 fully reversible cycles, confirming the stability and reversibility of using this process for adaptive thermal camouflage.

**Fig. 2. Dynamic IR performance.** (A and B) Real-time MWIR and LWIR images of device-2 and device-3 during the electrodeposition process, respectively. (C and D) Apparent temperature curves (central region) of the assembled devices in the MWIR and LWIR images during the electrodeposition process. (E) Apparent temperature difference curves between the central and peripheral regions of the assembled devices in the LWIR images during the electrodeposition process. (F) "Real-time" total IR reflectance spectra of device-3. (G) Maximum emittance tunability ranges of device-3, device-4, and device-5 in the MWIR and LWIR ATWs. (H) Cycling performance of device-3 (monitored by the apparent temperature curves at its central and peripheral regions in the LWIR images). (I) Total IR reflectance spectra of device-3 (in low-emittance state) and a nonspectrally selective low-emittance surface in the range of 2.5 to 25 $\mu$m. The yellow shaded region indicates the thermal radiation of a 330 K blackbody. The percentages (3, 15, 43.3, and 38.6%) shown in the figure represent the proportion of radiant energy in the range of 3 to 5 $\mu$m (MWIR), 5 to 7.5 $\mu$m, 7.5 to 13 $\mu$m (LWIR), and 13 to 25 $\mu$m, respectively. (J) Real temperature variations of device-3 (in low-emittance state) and a nonspectrally selective low-emittance surface during thermal measurements. Photo credit: Mingyang Li, National University of Defense Technology.
Furthermore, we noticed that the intrinsically high emittance of BaF$_2$ substrates in the range of 13 to 25 μm can radiate heat outside the two ATWs, thus providing additional radiative heat dissipation capability (37, 38) for our devices (Fig. 2J). To verify this point, we experimentally demonstrated the radiative heat dissipation capability of device-3 with a nonspectrally selective low-emittance sample. At an upward heating flux of 58.5 mW/cm$^2$, the equilibrium temperature of device-3 was increased by ~3.6°C after maintaining at its lowest emittance state for 25 min, which was ~2.4°C lower than that of the nonspectrally selective one (Fig. 2J).

**Multiplexing and enlarging**

To demonstrate the simplicity of multiplexing and enlarging of our devices, we constructed a three-by-three multiplexed IR switchable array and an enlarged independent device (fig. S11). The multiplexed array was constructed through patterning the nanoscopic Pt films during the evaporation process and adding controlling electric circuits when assembling the array. As shown in Fig. 3A and movie S2, by controlling the combination and electrodeposition time of its independent “pixels,” we enabled the multiplexed array to generate the letters “N,” “U,” “D,” and “T” with different apparent temperatures in the LWIR images. It is even simpler to enlarge the effective IR modulation size of our devices. By incorporating an additional conductive frame, the IR modulation size of our device was easily enlarged from ~5-cm$^2$ scale to ~20-cm$^2$ scale without obvious performance changes. As illustrated in Fig. 3B, the enlarged adaptive device with a quadrupled IR switching area of ~20 cm$^2$ exhibited almost the same dynamic IR modulation performance (such as large apparent temperature changes and high IR modulation uniformity) as the ~5-cm$^2$ scale devices. These two demonstrations showed the complex background adaptability (1, 2, 4, 39) and large-area feasibility (10) of our adaptive systems.

**Multisubstrate compatibility**

To further expand the camouflaging scenarios of our adaptive systems, we applied our metal-based dynamic IR modulation mechanism on rough and flexible surfaces. Thus, we replaced the polished BaF$_2$ substrates with rough BaF$_2$ substrates and polypropylene (PP) films to deposit nanoscopic Pt films. Because of the micrometer-sized roughness of the rough BaF$_2$ substrates and the relatively poor wettability of the PP films, thicker Pt films are required to form physically connected and electrically conductive films on these two substrates (fig. S12). Similarly, these nanoscopic Pt films also demonstrate strong Pt-induced absorption and partial transmission in the IR spectrum and offer sufficient electrical conductivities, indicating their potential IR modulation ranges in RSE system (figs. S13 and S14).

For fabricating rough surface–based adaptive device, we selected the rough BaF$_2$ substrate with nominal Pt thickness of 13 nm (~270 ohm square$^{-1}$) as the top electrode. Compared with the polished BaF$_2$-based device (device-3), which specularly reflect the external heat flux when switching to the low-emittance state (Fig. 4A, left), the rough BaF$_2$-based device can diffusely reflect the external thermal flux when switching to the low-emittance state and thereby reduce the total amount of thermal radiation received by the IR cameras (Fig. 4A, right). As illustrated in Fig. 4 (B and C), the specular component of the polished BaF$_2$-based device dominated ~96% of the total IR reflection after electrodepositing at ~2.2 V for 15 s, whereas the diffuse component of the rough BaF$_2$-based device accounted for ~95% of the total IR reflection after electrodepositing at ~2.5 V for 20 s. To further illustrate the advantages of this rough BaF$_2$-based device, we placed the polished BaF$_2$-based device and the rough BaF$_2$-based device on a 50°C hot plate and compared their IR responses under different external thermal flux using LWIR camera (Fig. 4D, fig. S15, and movie S3). In the absence of external thermal flux, the rough BaF$_2$-based device experienced an apparent temperature change of ~8.1°C in the LWIR images, which was smaller than that of the polished one (~20.7°C). This is because the cracks, gaps, and vertical regions of the rough BaF$_2$ surface are hard to be completely covered by the electrodeposited Ag film (fig. S15E), making it difficult for the rough BaF$_2$-based device to provide lower emittance states. However, as the external thermal flux was increased to 50°C, the rough BaF$_2$-based device still remained an obvious apparent temperature change of ~6.2°C in the LWIR images, whereas the polished BaF$_2$-based device only held an unremarkable apparent temperature change of ~1.3°C. This strongly indicates that the rough BaF$_2$-based device can not only diffusely reflect the outside thermal flux but also suppress its own IR radiation, showing its ability to effectively reduce the impact from external environment.

To fabricate the flexible surface–based adaptive device, we selected the PP film with nominal Pt thickness of 7 nm (~225 ohm square$^{-1}$)
as the top electrode (fig. S16 and movie S4). To demonstrate its dynamic IR performance under bending conditions, we attached the PP-based device on a cup filled with 50°C water. As shown in Fig. 4F and fig. S16, this flexible device exhibited large and uniform apparent temperature changes in the LWIR images, proving the viability of applying our metal-based IR modulation mechanism on flexible surfaces. Furthermore, because of the broadband IR transparency of the PP films, the PP-based devices exhibited IR tunabilities over the entire IR spectrum (Fig. 4F), showing their applications in both flexible and broadband IR modulation applications. As a result, these two rough and flexible adaptive variants illustrated the multishubstrate compatibility of our metal-based IR modulation mechanism and expanded its camouflageing scenarios to where diffuse IR modulation, ultrabroadband IR modulation, or flexibility is required.

Visible compatibility
Apart from the excellent IR modulation capabilities, our devices can be easily combined with structural color coatings to improve their visible compatibility. For demonstration, we incorporated a series of visible-wavelength-scale-thick chromium oxide (Cr₂O₃) layers (176, 234, 288, and 349 nm) between the BaF₂ substrates and the nanoscopic Pt films (Fig. 5A). Because of the thin-film interference effects of the Cr₂O₃ layers in the visible spectrum, the Cr₂O₃ “decorated” devices demonstrated various colors after depositing different thicknesses of Cr₂O₃ layers (Fig. 5B). As the thickness of the electrodeposited Ag films increased, the visible light waves reflected by the Ag films at the lower boundaries of the Cr₂O₃ layers gradually enhanced the thin-film interference effects. Therefore, the newly produced structural colors were shifted from relatively dark colors to more pronounced colors when thicker Ag films were electrodeposited, as shown in Fig. 5B and fig. S17. On the other hand, the Cr₂O₃ layers generated various colors in the visible spectrum, but they exerted little influence on the IR performance of our devices. As illustrated in Fig. 5C, because of the negligible IR absorption in the Cr₂O₃ layers, the Cr₂O₃-coated BaF₂ substrates underwent slight transmittance declines over the two IR ATWs. After assembling into devices, the “real-time” total IR reflectance spectra showed that as the Cr₂O₃ layers were increased from 0 to 349 nm, the Cr₂O₃ decorated devices only experienced slight

![Fig. 4. Multishubstrate compatibility.](image-url)
IR reflectance changes before and after electrodepositing for 15 s (Fig. 5D). By comparing with the “undecorated” device (device-3), the maximum emittance tunability ranges ($\Delta \varepsilon_{\text{MWIR}}$ and $\Delta \varepsilon_{\text{LWIR}}$) of the Cr$_2$O$_3$ decorated devices only decreased by 2.3 and 3.3% (176 nm), 7.7 and 3.3% (234 nm), 11 and 5.8% (288 nm), and 18.6 and 10% (349 nm), respectively (Fig. 5E). Moreover, the uniform color distribution of the Cr$_2$O$_3$ decorated devices in the real-time LWIR images illustrated that their IR modulation uniformity was not affected (fig. S18). These results present that simple optical designs can be integrated into our adaptive systems to acquire visible compatibility, making them more difficult to be detected in the daytime scenarios (5, 40).

**DISCUSSION**

We have demonstrated adaptive thermal camouflage devices by reversibly electrodepositing Ag on nanoscopic Pt films. Our devices exhibit large, uniform, and consistent IR tunabilities in both MWIR and LWIR ATWs. Remarkably, device-3 exhibits almost the largest MWIR and LWIR modulation ranges among previously reported IR modulation systems ($\Delta \varepsilon_{\text{MWIR}} \approx 0.77; \Delta \varepsilon_{\text{LWIR}} \approx 0.71$). Meanwhile, they have stable intermediate states (≥20 min), relatively good cycling performance (≥350 cycles), and additional radiative heat dissipation capability. By patterning the nanoscopic Pt films or by adding conductive grids, they can be easily multiplexed and enlarged, showing their complex background adaptability and large-area feasibility. The multisubstrate compatibility of our devices also enables rough surface–based and flexible surface–based adaptive variants, largely expanding their application scenarios to where diffuse IR modulation or flexibility is required. In addition, by incorporating a series of visible-wavelength-scale-thick Cr$_2$O$_3$ layers, they can be easily colored without affecting their dynamic IR performance, showing their visible compatibility. These devices inspire the next generation...
of adaptive thermal camouflage platforms that can precisely and quickly modulate thermal radiation, camouflage in multispectral detection, or adapt to complex environments, showing great promises for various military equipment, soldier protective systems, and facilities in the future. Last, the described technologies may also be applicable to many thermal radiation management–related technologies, including energy-efficient buildings (41, 42), personal thermoregulation clothes (16, 32, 43), and smart spacecraft components (11).

MATERIALS AND METHODS

Fabrication

Thin-film synthesis

The polished BaF$_2$ substrates (~1 mm in thickness) and the rough BaF$_2$ substrates (~1 mm in thickness) were cleaned by a stream of N$_2$ before the evaporation and sputtering process. The PP films (Chemplex Industries Inc.) with thickness of 12 µm were treated using an O$_2$ plasma cleaner to increase the oxygen-containing functional groups of their surface. The Pt films were directly evaporated on these substrates (polished BaF$_2$ substrates, rough BaF$_2$ substrates, PP films, and Cr$_2$O$_3$-coated BaF$_2$ substrates) using an electron-beam evaporation system (Kurt J. Lesker PVD 75) with a deposition rate of 0.02 nm s$^{-1}$ at room temperature. The nominal thickness of the Pt films was determined by extrapolation of the deposition rate, in turn calibrated using a quartz crystal oscillator. The chromium oxide (Cr$_2$O$_3$) layers were deposited on the polished BaF$_2$ substrates by radio-frequency magnetron sputtering of a pure Cr$_2$O$_3$ target (ZNXC Co.) under a power of 150 W. The working pressure is set to 2.0 Pa, and the Ar flow rate is set to 20 standard cubic centimeters per minute (sccm). The thickness of the Cr$_2$O$_3$ layers was determined by fitting the experimental data (Psi and Delta) from a spectroscopic ellipsometer (alpha-SE Ellipsometer; J. A. Woollam Co.).

Gel electrolyte preparation

The gel electrolyte was prepared by mixing 0.5 mM AgNO$_3$ (Sigma-Aldrich), 0.1 mM CuCl$_2$ (Sigma-Aldrich), 2.5 mM tetrabutylammonium bromide (TBABr; Sigma-Aldrich), and 10 weight % polyvinyl alcohol [PVA; Sigma-Aldrich; molecular weight (M_w) = 89,000 to 98,000] in a 100-ml dimethyl sulfoxide (DMSO; Aladdin) solution.

Independent device assembly

The independent adaptive devices were constructed by using the Pt evaporated BaF$_2$ substrates with Pt thickness of 3 nm as the working electrodes and ITO-coated polyethylene terephthalate (PET-ITO; ~14 ohm square$^{-2}$; Zhuhai Kaivo Co.) as the counter electrodes. To make uniform electrical contact, conductive silver paint (SPI Co.) was applied across the perimeter of both the working and counter electrodes. Next, the conductive silver paint was sealed with epoxy to prevent it from contacting with the gel electrolyte. Then, filter papers (Aladdin) completely saturated with the gel electrolyte were added between the Pt evaporated BaF$_2$ substrates and the PET-ITO electrodes, providing mechanical support and an interelectrode spacing of ~150 µm for these devices. Last, epoxy and Kapton tapes were used to seal the edges of these devices to prevent electrolyte leakage.

Multiplexed device assembly

First, the evaporated Pt film formed a three-by-three array by attaching Kapton tapes onto a 6 cm × 6 cm BaF$_2$ substrate before the Pt evaporation process. Next, the Kapton tapes were removed and the controlling circuits were added onto the patterned Pt array by coating conductive silver paint (sealed by epoxy). Then, similar controlling circuits (sealed by epoxy and Kapton tapes) were also added onto a prepatterned PET-ITO electrode. After that, filter paper (Aladdin) completely saturated with the gel electrolyte was added between the patterned Pt evaporated BaF$_2$ substrate and the PET-ITO electrode. Last, epoxy and Kapton tapes were used to seal the edges of this multiplexed device to prevent electrolyte leakage.

Enlarged device assembly

First, the Pt film was evaporated onto a 6 cm × 6 cm BaF$_2$ substrate. Next, an additional cross-shaped conductive frame was added onto the center of the Pt evaporated BaF$_2$ substrate and conductive silver paint (SPI Co.) was applied across the perimeter of the Pt evaporated BaF$_2$ substrate. Then, both the cross-shaped conductive frame and the conductive grid were sealed by epoxy and Kapton tapes. After that, filter paper (Aladdin) completely saturated with the gel electrolyte was added between the Pt evaporated BaF$_2$ substrate and the PET-ITO electrode. Last, epoxy and Kapton tapes were used to seal the edges of this enlarged device to prevent electrolyte leakage.

Characterization

IR spectroscopy measurements

The total IR reflectance spectra of the samples were measured with a Fourier transform IR (FTIR) spectrometer (Bruker Vertex 70) equipped with an upward-looking mid-IR integrating sphere (A562), which featured a sample port with a diameter of ~2.1 cm. The measurements were performed at an illumination angle of 12° over a wavelength range of 2.5 to 25 µm and referenced to a diffuse gold standard (Bruker). The total IR transmittance spectra were likewise measured, with the samples placed at the mouth of the integrating sphere. The total IR absorbance spectra were calculated according to the following equation: Total IR absorbance (%) = 100% − Total IR transmittance (%) − Total IR reflectance (%). The “real-time” total IR reflectance of the assembled devices was also measured using the FTIR Spectrometer equipped with the integrating sphere while using the PARSTAT 4000 Advanced Electrochemical System (Princeton Applied Research, USA) to perform the electrodeposition steps and the protective currents. The “real-time” specular IR reflectance spectra of the assembled devices were measured using the FTIR Spectrometer equipped with a variable angle specular reflectance accessory (VeeMAX III; Pike Technologies) (referenced to a standard gold film, Bruker) while using the electrochemical system to perform the electrodeposition steps and the protective currents. The “real-time” diffuse IR reflectance spectra were calculated according to the following equation: Diffuse reflectance (%) = Total reflectance (%) − Specular reflectance (%). In all cases, the measurements were performed at ~20°C and the relative humidity was maintained at ~45%.

Ultraviolet-visible–near-IR measurements

The ultraviolet-visible (UV-Vis)–near-IR (NIR) transmittance spectra of the samples with a wavelength range of 0.3 to 2.5 µm were measured using an UV-Vis–NIR spectrophotometer (Hitachi U-4100) equipped with a diffuse integrating sphere. The “real-time” visible reflectance spectra of the Cr$_2$O$_3$ decorated adaptive devices were measured with an Ocean Optics OFS-2500 spectrometer coupled with an Ocean Optics halogen light source (LS-3000) while using the PARSTAT 4000 Advanced Electrochemical System (Princeton Applied Research, USA) to perform the electrodeposition steps and the protective currents.

Sheet resistance

The sheet resistance of the evaporated Pt films was measured using a four-probe resistivity measurement system (RTS-9, Guangzhou, China).
**Digital and IR camera imaging**

Photographs of the samples were obtained with a Nikon D7100 digital camera (visible). The color three-dimensional image of the rough BaF$_2$ surface was obtained with a digital microscope system (VHX-2000C). The MWIR and LWIR images were recorded using IR cameras working in the range of 3.7 to 4.8 µm (FLIR SC7300M) and 7.5 to 13 µm (FLIR T420), respectively (their predefined emittances were both set to 1.0). During all measurements, the room temperature was maintained at ~20°C and the relative humidity was maintained at ~45%. For analysis, the apparent temperature curves of the central and peripheral regions of the devices in MWIR and LWIR images were extracted by a box measurement tool and the line measurement tool in the FLIR software packages (FLIR Tools V 5.7 and FLIR ResearchIR Max 4.0). The videos were captured through live streaming to a computer with the FLIR software packages and recorded with the Bandicam Screen Recording software package.

**Spectroscopic ellipsometry measurements**

The spectroscopic ellipsometry measurements of the Cr$_2$O$_3$-coated BaF$_2$ substrates were taken from 380 to 900 nm at angles of 70° and 75° using a spectroscopic ellipsometer (alpha-SE Ellipsometer; J. A. Woollam Co.). The optical constants and the film thickness were fitted from the experimental data (Psi and Delta) in the CompleteEASE software. The IR spectroscopic ellipsometry measurements of the polished BaF$_2$ substrate were taken from 1.7 to 30 µm at angles of 70° and 80° using an IR spectroscopic ellipsometer (IR-VASE MARK II Ellipsometer; J. A. Woollam Co.). The optical constants of the polished BaF$_2$ substrate were fitted from the experimental data (Psi and Delta) in the WVASE software.

**SEM observation**

The highly magnified surface morphologies of the nanoscopic Pt films, the Ag electrodeposited ITO electrode, and the Ag electrodeposited 3-nm Pt film were observed using an ultrahigh resolution field-emission scanning electron microscope (UHR FE-SEM; Regu-losup8100; Hitachi Co.). The Pt films were cleaned using an UV ozone cleaner (Hitachi Co.) for 5 min before putting into the SEM chamber. The Ag electrodeposited ITO electrode and the Ag electrodeposited Pt film were cleaned in DMSO and ethanol solutions and subsequently dried under a stream of N$_2$ before putting into the SEM chamber. The energy-dispersive spectroscopy (EDS) characterization was performed on an X-Max EDS unit (Oxford Instruments).

**Elemental analysis**

X-ray photoelectron spectroscopy (XPS; Thermo ESCALAB 250Xi) was performed using a monochromatic Al Kα source (1486.6 eV).

**Atomic force microscope measurements**

The surface morphologies of the samples were examined with an atomic force microscope (Bruker Dimension Icon).

**Grazing incidence x-ray diffraction measurements**

Grazing incidence x-ray diffraction (GIXRD) was performed on a Bruker D8 ADVANCE x-ray diffractometer with a Cu Kα x-ray source. The instrument was operated in parallel beam geometry, and measurements were collected with a 20 scan axis. GIXRD patterns were collected from 10° to 90° 2θ, with a step size of 0.02° and a scan speed of 2° min$^{-1}$. Omega value of 0.5° was used for all these thin-film samples to ensure high intensity.

**Electrical control**

The measurement in the three-electrode RSE system and the electrical control of the assembled devices were performed using the PARSTAT 4000 Advanced Electrochemical System (Princeton Applied Research, USA).

**Heat dissipation capacity measurements**

Device-3 and the nonspectrally selective sample were mounted onto the PET side of an ITO-coated PET film (150 µm in thickness and 35 mm in length, covered with an ITO film with a sheet resistance of ~ 14 ohm square$^{-1}$), whereas a dc power supply was used to electrify the ITO film (58.5 mW/cm$^2$). A K-type sticker thermocouple and a multichannel temperature recorder (JK808; Jinko Co.) were mounted onto the backside of device-3 and the nonspectrally selective sample to record the temperatures of the samples every 1 s. A silica (SiO$_2$) aerogel brick was placed under the ITO-coated PET to avoid downward heat conduction and to ensure the heat generated by the ITO film transferred upward only. The nonspectrally selective sample was prepared by assembling a Pt deposited BaF$_2$ substrate with Pt thickness of 25 nm (the Pt side is upward) into the device for comparison.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/22/eaba3494/DC1

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