Article

Photonic nanostructures mimicking floral epidermis for perovskite solar cells

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SUMMARY

Here, we report photonic nanostructures replicated from the adaxial epidermis of flower petals onto light-polymerized coatings using low-cost nanoimprint lithography at ambient temperature. These multifunctional nanocoatings are applied to confer enhanced light trapping, water repellence, and UV light and environmental moisture protection features in perovskite solar cells. The former feature helps attain a maximum power conversion efficiency of 24.61% (21.01% for the reference cell) without any additional device optimization. Added to these merits, the nanocoatings also enable stable operation under AM 1.5G and UV light continuous illumination or in real-world conditions. Our engineering approach provides a simple way to produce multifunctional nanocoatings optimized by nature’s wisdom.

INTRODUCTION

As our world witnesses severe climate change, a long overdue transition to alternative energy sources is imperative. Solar cells experience unprecedented growth; however, a major bottleneck to achieve power conversion efficiencies (PCEs) close to the Shockley-Queisser limit is the reflection losses at the transparent glass/air interface.1 For example, in solar panels, nearly one-third of the incident solar irradiation is reflected, thus limiting the light-to-current conversion.2 Several light management schemes, which include textured surfaces and antireflection coatings (ARs) placed on the transparent side of the solar cell, have been developed.3,4 They aim to (1) redirect the light rays or trap them by total internal reflection, thus improving light incoupling at the front surface,5 (2) enhance light absorption of semiconductors in weakly absorbing wavelength regions,6 and (3) improve light management in solar cells, which includes photonic crystals,7 diffraction gratings,8 plasmonic nanostructures,9 nanowires,10 metamaterials,11 randomly textured scattering surfaces,12 and surface textures like honeycomb structures13 or inverted pyramids.14 These light management schemes have been developed for thick inorganic semiconductor solar cells and usually rely on vacuum deposition methods and complex nanopatterning schemes. Despite their success, they need to be modified (i.e., become simpler, lighter, and cost effective) in order to become compatible with low-cost, thin-film, solution-based photovoltaics such as organic and perovskite solar cells.

In the search for low-cost alternatives, researchers have also focused on biomimetic light-harvesting structures inspired by animals or plants. The former have attracted...
increasing attention, and prominent examples are antireflective surfaces mimicking the corneas of moth eyes and the transparent wings of cicada, blue *Morpho* butterfly, and hawk moths.\textsuperscript{7,15,16} Natural moth-eye structures consist of ordered conical protrusions 250 nm in height with spaces of 200–250 nm. Analogs of the moth-eye structure have been widely reproduced by lithographic techniques and used as ARs on solar cells and glass windows.\textsuperscript{17–19} Notably, they also possess self-cleaning properties, as their nanoscopic surfaces minimize droplets’ adhesion to the substrate (static water contact angle values over 150°).\textsuperscript{20,21} Still, their water repellence remains inferior compared with the superhydrophobic archetypal of natural *Nelumbo nucifera* (lotus) leaves (water contact angle higher than 170°).\textsuperscript{22}

However, relatively little research has been conducted on light-harvesting structures mimicking plant leaves and flowers for solar cells, although evolution has found remarkable ways to optimize their light management features for their survival. For example, the petal adaxial epidermis (the epidermis orientated toward potential pollinators) of many angiospermae consists of conical cells similar to those of the corneal of moth eye. These effectively trap light, intensify their color, and warm the nectar, thus increasing their attractiveness to pollinators.\textsuperscript{23,24} Flower petal epidermis also possesses superhydrophobic properties originating from nanostructuring.\textsuperscript{25,26} Based on these promises, some recent papers report photonic structures replicated by flowers for thin-film solar cells.\textsuperscript{27–31} These reports demonstrate enhanced light management in the case of replicas with a high aspect ratio approaching or even exceeding 1.0.\textsuperscript{27,29}

Here, we replicate a series of nanocoatings from floral petal epidermal cells of various species, in particular, *Ranunculus repens*, *Anchusa officinalis*, *Aubrieta deltoidea*, *Geranium endressii*, and *Antirrhinum majus*. We verify the proposed correlation between the AR function and the aspect ratio of photonic structures.\textsuperscript{27} We also demonstrate a link between AR, water repellence, and nanomorphology. We apply these nanocoatings in perovskite solar cells (PSCs), which attain a maximum PCE of 24.61% (21.01% for the reference cell) without any additional device optimization.\textsuperscript{32–36} They also present excellent stability under continuous illumination with AM 1.5G or UV light (254 nm) and in real-world conditions, an indication that nanostructures inspired by nature can benefit many technological areas including emerging solar cell technologies, such as PSCs.

**RESULTS AND DISCUSSION**

**Replication and properties of photonic structures**

We selected flowers with colors spanning from pale yellow (*R. repens*) to intense burgundy (*Antirrhinum majus*), as color is related to floral antireflection function (Figure S1).\textsuperscript{37} We replicated their petal epidermal cells by using soft UV nanoimprint lithography (soft UV-NIL) and commercially available materials such as polydimethylsiloxane (PDMS) and UV photocurable adhesives (resins). The details for the preparation of the replicas are given in the experimental procedures. In brief, the negative structure of the petal cells was first patterned in a PDMS master, which was used as a mold for the replication of floral cells on a liquid UV light polymerized acrylate urethane adhesive (Dymax, DYM 6–621). Afterward, the resin was poured onto the PDMS slab, irradiated with a mercury lab for 5 min, and then removed from the slab. No primer was applied before dropping the resin onto the PDMS, and the process was accomplished in ambient conditions.

The replicated photonic structures present profound differences as shown in scanning electron microscopy (SEM) images presented in Figures 1 and S2. The replica
of *R. repens* consists of dense conical nanoprotrusions 60 nm in height and 300 nm in their basis diameter (aspect ratio: 0.2). Films replicated from *A. officinalis* appear quite compact and are composed of densely packed papillate nanoprotrusions with a flat top surface similar to those of *A. deltoidea* and *G. endressii*; however, the nanoprotrusions in *G. endressii* replica are well separated between them. Moreover, the *Antirrhinum majus* replica consists of well-separated hierarchical conical nanostructures (around 360 nm in height and 450 nm in basis diameter, aspect ratio: 0.8), which feature structured peripheries with dimensions much smaller than the wavelengths of visible light (i.e., sub-wavelength). Notably, the petal adaxial epidermis of *A. majus* presents great similarity with both moth-eye conical nanostructures and lotus leaf conical hierarchical structures.22,27

The reflectivity of nanocoatings replicated from the adaxial petal epidemics of the selected floral species against the calculated aspect ratio of the petal nanostructures is shown in Figure S3A (angle of incidence [AOI] = 80°). The reflectivity of the uncoated glass is about 40% (also shown in this figure), and a monotonic decrease upon coating with photonic structures of increasing aspect ratio is observed, in agreement with previous reports.27 The nanocoatings consisting of well-separated, individual protrusions with high aspect ratio and especially the conically shaped structures replicated by *A. majus* present the lower reflectivity and higher transmittance (Figure S3). This can be explained by taking into account the Fresnel equation,

\[ R = \left( \frac{n_1 - n_2}{n_1 + n_2} \right)^2, \]  

(Equation 1)

which describes that the specular reflection at an interface between two media (where \( n_1 \) and \( n_2 \) are the refractive indices of the media)38 should be changed with textured or rough interfaces. This is because the textured interface behaves as an effective medium with a gradually varying refractive index.39 Given this continuous
A refractive index gradient, the incident light experiences no abrupt change in the refractive index, resulting in lower specular reflectance. In particular, the Fresnel equation can be approximated as

$$R = \left( \frac{n_{\text{eff}} - n_g}{n_{\text{eff}} + n_g} \right)^2,$$

(Equation 2)

where the effective refractive index can be calculated as

$$n_{\text{eff}} = \left[ f n_n^{2/3} + (1 - f) n_p^{2/3} \right]^{3/2},$$

(Equation 3)

where $f$ is the filling factor dependent on the geometry and aspect ratio of the textured structures. Tuning the geometry of the structures alters the effective refractive index, hence suppressing the specular reflectance on a textured or rough surface. Additionally, in photonic structures with sub-wavelength dimensions, light rays are scattered and tend to bend progressively, therefore changing their path and being trapped inside the semiconductor (as illustrated in Figure S4). *A. majus* replica consists of conically shaped features decorated with small nanofeatures at their periphery, and it is thus expected that (1) suppression of the specular reflection at the conically textured interface and (2) enhanced Rayleigh scattering at the nanofeatures will synergistically contribute to the low reflectance and enhanced transmittance of this flower replica.

Indeed, the photonic structure exhibits extremely low reflectivity for the wide range of UV and visible light wavelengths (300–800 nm; Figure 2A) and for a varying AOI (Figure 2B). Compared with the reference sample, which is coated with a plain resist, the specular reflectance at the flower structure/air interface is reduced from 4% to
0.1% for close to normal incidence; the difference further increases for higher AOI. Besides the low specular reflection, an effective light management scheme should also present negligible reflection to s- and p-polarized light having the electric field perpendicular and parallel to the incidence plane, respectively. A. majus replica exhibits very low reflectivity for both s and p polarizations over a broad spectral and AOI range, with the reflectance being below 0.1% for the entire visible spectrum at low AOI values (Figure 2C). The broadband and omnidirectional AR properties of our floral replica along with ease of fabrication and integration to any substrate are key factors demonstrating its suitability for solar cells. With their transmittance to be around 97% in the visible wavelength range, these nanocoatings are suited for application in the front transparent device cover. Notably, due to their adequate absorption in the UV part of the spectrum, they could act as protective buffers for the absorber (i.e., perovskite) layer, preventing degradation photoreactions.44–48

A critical factor for any AR coating applied to the front side of solar cells is their self-cleaning properties originating from water repellency.49 Optical microscopy images of water droplets on plain glass, glass covered with flat resin, and flower replicas (Figures 2D and S5) present distinct differences. Floral-replicated nanocoatings exhibit ultra large contact angle values over 170° compared with 114° for flat resin and 32.03° for glass. A. majus hierarchical nanocoating features a static contact angle of 179.8°, larger than that of the natural lotus leaf (i.e., around 170°). The ultra-hydrophobic properties of this replica can be explained by taking into account the model proposed by Cassie-Baxter50 for chemically heterogeneous (composite) surfaces (i.e., air within a porous or textured homogeneous surface). It is based on the consideration that a liquid droplet placed on a textured or rough feature rests on a heterogeneous composite air-solid surface. The apparent contact angle for a composite surface is given by

\[ \cos \theta_{\text{comp.}} = f_1 \cos \theta_1 + f_2 \cos \theta_2, \]  

(Equation 4)

where \( f_1, \theta_1, \) and \( f_2, \theta_2, \) are the fractional area and contact angle of the two materials, respectively (with \( f_1 + f_2 = 1 \)). This model considers that the liquid droplet only touches the tip of the peaks of textured or rough solids, and, consequently, air pockets are formed between the droplet and the substrate (Figure S6). Considering that between the textured solid surface and the liquid droplet only air exists, the cosine of the angle \( \theta_2 \) becomes \(-1\), and the above equation can be written as

\[ \cos \theta_{\text{comp.}} = f_1 (\cos \theta_1 +1) -1. \]  

(Equation 5)

In that case, as the fraction of air increases, and, consequently, \( f_1 \) approaches zero, a contact angle approaching 180° is predicted for the composite. In addition, this model also predicts that the water drop can easily roll down from the surface and that the contact angle hysteresis is very small. A contact angle hysteresis of 1° is obtained for A. majus replica, indicating the ultra-hydrophobic properties of this structure. This endows the surface with self-cleaning properties as shown in Figure S7 and Videos S1 and S2, where flat resin (Video S1) and flower-replicated (Video S2) coatings on glass are tested for their self-cleaning function. Both were covered with yellow powder-like dust. Notably, the powder particles were clearly removed after dropping the water droplets at the surface without any residue. On the other hand, sufficient dust remains on the flat resin-coated glass.

A. majus replica on glass exhibits a solar-weighted transmittance (SWT) of ~95.6% significantly higher than that of the flat resin (~90.3%). This value was recovered after
the cleaning procedure (Figure 2E). SWT expresses the ratio of the photons transmitted to the total photons; its high value in the case of flower replica indicates potentially improved light harvesting from the absorber layer. This is verified by the enhancement in simulated absorption spectra of PSCs based on triple cation halide perovskite emitter (CsPbI$_3$)$_{0.05}$[FAPbI$_3$]$_{0.83}$(MAPbBr$_3$)$_{0.17}$ (Figure 2F).

Application to PSCs

We fabricated and tested two sets of PSC devices: those without the AR coating on the front glass side (termed hereafter as control devices) and those with the AR. The devices include a mesoporous titanium dioxide (TiO$_2$) electron-transport layer and a Spiro-MeOTAD hole-transport layer (Figure S8). Between the perovskite absorber and both charge transport layers, two-dimensional atomic-thick graphene nanosheets are inserted to passivate the interfaces and endow the device with high mobility. The device using flat resin is referenced as a control cell, whereas that with the flower replica is termed a flower cell. Besides the AR nanocoating (either flat resin or $A.~majus$ replica), these cells are completely identical, indicating that any absorption difference is due to a mere antireflective effect.

The devices exhibit identical diode characteristics when measured in the dark (Figure 3A), as expected. Figures 3B and 3C present their current density-voltage (J-V) characteristics under AM 1.5G-simulated light illumination and external quantum efficiency (EQE) spectra, respectively. The effect of light trapping in the flower-replica-coated cell is manifested as a ~6% increase in short-circuit current density ($J_{SC}$) from 23.29 for the control cell to 24.62 mA cm$^{-2}$ for the flower-based device (Table S1). This results in an increase in PCE from 21.01% to 22.20% (22.18% at maximum power...
point [MPP] tracking; Figure S9). Notably, the optimized device also presented negligible hysteresis (Figure S9). The high efficiency of the flower cells was also reproducible (Figure S10). The photocurrent enhancement is reflected in the EQE curves (Figure 3C); a clear increase at wavelengths below 500 nm and over 700 nm, in agreement with the calculated absorption enhancement (Figure 2F), can be obtained by subtracting the EQE spectra of flower and control cells. This improvement is in agreement with the enhanced photocurrent in a wide range of light incident angles (Figure 3D) and the increased charge-carrier generation rate by nearly one order of magnitude in the flower compared with the control device (Figure 4).

However, this improvement cannot be explained only by the suppression in specular reflection at normal incidence through applying the photonic structure on the glass front side (a decrease in the specular reflectance of about 4% was manifested). Even if we assume perfect light in-coupling properties, the maximum enhancement of 4% in specular reflectance is lower than the 6% enhancement in PCE. Consequently, an additional optical effect that also enhances light harvesting should be sought. To unravel a potential second optical effect of flower replica, we performed additional transmission measurements by illuminating the flower replica/glass sample from the back side (Figure S11). By comparing the transmittance measured by illuminating the front (Figure S3B) and back (Figure S11) sides, we can conclude that the flower structure also presents retro-reflection properties (that is, back reflection at the glass/flower interface; Figure S12). As a result, some light rays that are transmitted through the flower replica/glass interface toward the PSC but they are reflected at the planar interface of glass with the solar cell will be retro-reflected (back reflected) at the glass/flower interface toward the solar cell again.

The flower replica also enabled excellent stability upon continuous illumination in nitrogen (Figure 5A). It is observed that the cell embedding the replica was very stable upon AM 1.5 G illumination for 1,000 h in nitrogen without any encapsulation. However, the control cell bearing the plain resin coating was also quite stable, indicating that the high device stability originates from the resin itself (probably from its high absorption in the UV part of the spectrum). Besides the study in nitrogen, the device’s self-cleaning properties were also investigated (Figures 5B and 5C). After being covered with a sufficient amount of dust, control and flower cells were rinsed with actual rain drops. Flower-based PSC nearly recovered its initial photocurrent...
(24.37 from 24.62 mA cm\(^{-2}\), which corresponds to a 1% reduction), while the control device exhibited a 3% drop in \(J_{SC}\) (22.56 from 23.29 mA cm\(^{-2}\)). As a result, the control cell undergoes sufficient reduction (20.40% from 21.01%), whereas the flower cell maintains its high efficiency (21.91% from 22.20%) owing to the excellent self-cleaning property of the nanostructured coating compared with the plain film consisting of the same resin (Figure S13). Given also the ultra hydrophobic effect of the textured flower coating, we further applied it as an encapsulate buffer on both sides of the cells and performed an aging study to verify the stability of PSCs under real-world conditions. The devices were placed on the terrace of the Department of Information Display building in Seoul (South Korea) for 14 days, thus experiencing real outdoor operating conditions. PCE was measured once a day.

Despite the success of *A. majus* replica as AR nanocoating, these PSCs still have relatively moderate efficiencies compared with the recently achieved 25.8% in single-junction devices using pseudo-halide anion engineering.\(^{54,55}\) We investigated the effect of the refractive index (RI) value of the UV-curing adhesive used for the fabrication of coatings. DYM 6–621 (from Dymax) is an acrylate urethane with an RI between 1.575 and 1.615.\(^{56}\) This value is expected to be increased by 1%–4%
when the oligomer is UV cured (Figure S16A). We tested a different UV-curing adhesive, namely NOA68, from Norland Products. According to the supplier, this material exhibits a low RI of 1.54 (very close to that of common glass) when it becomes a UV-cured polymer. This was also verified by our measurements. When we replicated A. majus on NOA68 and used it on the front glass side as an AR coating, the PCE of the device was increased to 24.61% (24.13% stabilized) (Figures 6A and 6B). The device also presented negligible hysteresis (Table S2; Figure S17). The high increase in PCE resulted from an additional $J_{SC}$ enhancement in JSC (from 24.62 to 26.11 mA cm$^{-2}$). The EQE curve shows high values approaching 100% in most of the wavelengths of the visible spectrum (Figure 6C). The integration between the AM 1.5G photon flux with the incident PCE (IPCE) spectrum delivers a calculated photocurrent of 26.25 mA cm$^{-2}$ (which is close to that measured experimentally, $J_{SC} = 26.11$ mA cm$^{-2}$). This additional enhancement in photocurrent, besides the suppression of specular reflectance at the conical structures and effective Rayleigh scattering caused by the sub-wavelength nanofeatures, also stems from the close matching of the RI between NOA68 and glass substrate, which eliminates the back reflectance of rays reaching the respective interface and ensures transition of light rays into the glass substrate (Figure S16B). In addition to the $J_{SC}$ enhancement, a small improvement in VOC value (from 1.13 to 1.16 V) is obtained, which can be explained by the photodiode equation:

$$V_{OC} = \frac{kT}{q} \ln \left( \frac{J_{SC}}{J_0} + 1 \right), \quad (\text{Equation 6})$$

where $k$ is the Boltzmann constant, $T$ is the absolute temperature, $q$ is the elementary charge, and $J_0$ is the device reverse current. In addition, we observe an improvement
in the FF value in the champion cell, which is also related to the enhanced $V_{OC}$ through the empirical formula proposed by M.A. Green:\textsuperscript{58}

$$\text{FF} = \frac{\text{FF}_{\text{oc}} - (\ln \text{FF}_{\text{oc}} + 0.72)}{\text{FF}_{\text{oc}} + 1}, \quad \text{(Equation 7)}$$

where \(\text{FF}_{\text{oc}} = \frac{q}{kT}V_{\text{oc}}\), is defined as “normalized \(V_{\text{oc}}\).”

Because NOA68 (but also DIM6-621) strongly absorbs UV light with wavelengths below 350–380 nm (as indicated by the increase in their extinction coefficients in Figure S16B), we performed a UV degradation study of PSCs using plain resins and flower replicas formed by both DIM6-621 and NOA68. We compared these devices with PSCs embedding no coating. The devices were illuminated with 254 nm light inside a nitrogen-filled glove box for 1,000 h. From Figure 6D, it becomes evident that all the devices using plain or flower coatings exhibit sufficient resistance to UV degradation. On the contrary, the reference cell without any coating presented a moderate decline in efficiency; an indication that the coatings also acted as UV-protected buffers for the PSCs due to their high absorption at the wavelength range of interest. However, their UV or visible light protection property is not strictly related to nanotexturing.

In conclusion, we present a facile approach to fabricate multifunctional textured coatings by mimicking the adaxial epidermis of floral petals. We show that coatings consisting of hierarchical conical structures decorated with small nanofeatures at their peripheries combine omnidirectional antireflection, excellent water repellence, and moisture/UV light barrier functionality. Applying these coatings to PSCs enables enhanced efficiencies of over 24% through improved light trapping and an increase in photocurrent. They also endow the device with resistance to degradation caused by continuous illumination, environmental moisture, and UV light. Our work identifies that mimicking the functions of adaxial epidermal cells of flower petals and combining them with appropriate artificial materials to engineer novel nanocoatings could become a synergy with great potential.

**EXPERIMENTAL PROCEDURES**

**Resource availability**

**Lead contact**

Further information and requests should be directed to and will be fulfilled by the lead contact, Maria Vasilopoulou (m.vasilopoulou@inn.demokritos.gr).

**Materials availability**

All materials generated in this study are available from the lead contact without restriction.

**Data and code availability**

The published article and its supplemental information include all data generated or analyzed during this study.

**Materials**

The organic cations for the preparation of perovskite precursor solutions were purchased from Dyesol, the lead compounds from TCI, and CsI from abcr GmbH. Monolayer graphene was purchased from Graphene Supermarket. (2,2′,7,7′-Tetrakis[N,N-di(4-methoxyphenyl)amino]-9,9′-spirobifluorene) (Spiro-OMeTAD) was purchased from Merck; bis(trifluoromethylsulfonyl)imide lithium salt (Li-TFSI) and 4-tert-butylpyridine (TBP) were purchased from Sigma-Aldrich; tris(2-(1H-pyrazol-1-yl)-4-tert-butylpyridine)-cobalt(III) tris(bis(trifluoromethyl sulfonyl)imide) (FK209) was obtained from Dynamo.
adhesive DYM 6–621 was purchased from Dymax. UV-curing adhesive Norland Optical Adhesive NOA68 was obtained from Norland Products.

Replication of flower petal adaxial epidermal cells

Fresh petals were collected from Jardim Botanico Curitiba, Brazil. In particular, petals of wild-type (not mutations, where any) *R. repens*, *A. officinalis*, *A. deltoidea*, *G. endressii*, and *A. majus* were selected for an initial assessment. Healthy petals were carefully chosen, rinsed with water to remove adhering particles, and cut into 3 × 3 cm samples for replication. A poly(dimethyl siloxane) (PDMS) curing kit (Sylgard 184 silicone kit, Essex Group) dissolved in hexane was used to form a 0.05 g/mL PDMS solution. Ten µL PDMS solution was poured over the petal and quickly spread by capillary forces. Afterwards, solvent evaporation took place by curing the samples at 60°C for 4 h. To easily detach the PDMS slab from the petal, we sprayed it with chloroform, which caused swelling. The removed PDMS was allowed to dry at room temperature for 2 h to return to its normal state. A negative flower replica was thus obtained. The chosen petal nanostructure was next replicated by dropping 100 µL of a commercially available photoresin (either Dymax UV-light curing adhesive, DYM 6–621 or NOA68, Norland Products) onto the substrate. The photo-curable photoresists were in a liquid phase and required no primer when poured onto the PDMS slab. They were subjected to a broadband exposure with a mercury (Hg) lamp (approximate dose >1 J cm⁻²) while also being pressed on the PDMS slab from the center outward to remove access to oxygen and prevent oxygen inhibition during the 5 min of the curing process. Finally, the PDMS slab was slowly detached from the cured resin. The best results were accomplished at temperatures of 20°C–25°C and relative humidity of 40%–46%.

Device fabrication and characterization

Details for the device fabrication and measurements are given in the supplemental experimental procedures.

Thin-film measurements

SEM was performed on a ZEISS Merlin for Materials. The wettability of the petals was measured using static contact angle (CA) measurements (Dataphysics SCA 2.02, Filderstadt, Germany) taken by dropping 5 µL of de-mineralized water on the samples. The CAs were evaluated automatically using the Laplace-Young fitting algorithm. The specular reflectivity for varying angles of incidence was measured in a double-rotation stage (Huber), in which the sample was mounted in the inner stage and a power meter (Thorlabs, PM300) on the outer stage. An argon-krypton laser source and a ColorPol VIS500 linear polarizer (10 mW on the sample) were used at 514 nm wavelength. The beam spot size on the sample was 1 mm in diameter.

FDTD simulation

The finite-difference time-domain (FDTD) simulation was conducted with the Lumerical FDTD software package using plane waves with 300–800 nm wavelengths. The power absorption was calculated through the equation

\[ P_{\text{abs}} = -0.5\omega|E|^2 \text{imag}(\varepsilon) \]  

(Equation 8)

\( P_{\text{abs}} \) refers to the absorbed power per unit volume, \( \omega \) to the angular frequency, \( E \) to the electrical field, and \( \text{imag}(\varepsilon) \) is the imaginary part of the dielectric permittivity.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.xcrp.2022.101019.
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AUTHOR CONTRIBUTIONS

M.V., W.J.d.S., A.S., H.P.K., B.S.K., Y.R., A.E.X.G., J.C., F.K.S., L.C.P., D.D., P.A., T.S., and A.F. performed the device experiments. M.F. selected and provided flower petals and relevant experiments. M.V., W.J.d.S., J.J., N.G., M.K.N., Y.-Y.N., and A.R.B.M.Y. conceived the idea and supervised the experiments. M.V., N.G., A.F., and A.R.B.M.Y. wrote the paper with contributions from all authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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