



ENGINEERING

Monolithically integrated neuromorphic electronic skin for biomimetic radiation shielding

Jong Min Lee^{1†}, Sung Woon Cho^{2†}, Chanh Jo¹, Seong Hwan Yang¹, Jaehyun Kim³, Do Yeon Kim⁴, Jeong-Wan Jo⁵, Jong S. Park⁴, Yong-Hoon Kim^{6*}, Sung Kyu Park^{1*}

Melanogenesis, a natural responsive mechanism of human skin to harmful radiation, is a self-triggered defensive neural activity safeguarding the body from radiation exposure in advance. With the increasing significance of radiation shielding in diverse medical health care and wearable applications, a biomimetic neuromorphic optoelectronic system with adaptive radiation shielding capability is often needed. Here, we demonstrate a transparent and flexible metal oxide–based photovoltaic neuromorphic defensive system. By using a monolithically integrated ultraflexible optoelectronic circuitry and electrochromic device, seamless neural processing for ultraviolet (UV) radiation shielding including history-based sensing, memorizing, risk recognition, and blocking can be realized with piling the entire signal chain into the flexible devices. The UV shielding capability of the system can be evaluated as autonomous blocking up to 97% of UV radiation from 5 to 90 watts per square meter in less than 16.9 seconds, demonstrating autonomously modulated sensitivity and response time corresponding to UV environmental conditions and supplied bias.

INTRODUCTION

Neuromorphic engineering, inspired by the neural structure and functions of the human brain, presents a promising approach for creating dynamic sensory systems adept at recognizing complex external stimuli and autonomously driving responses (1–4). In this regard, there has been growing interest in the advancement of sensory systems that can biomimetically process diverse information such as auditory (5, 6), olfactory (7, 8), tactile (9–11), and visual stimuli (12–14). In addition, the neuromorphic computing capabilities observed in these sensor systems have been enhanced by the neural network algorithms, resulting in lower power consumption, simplifying circuitry, and reduced data redundancy (15, 16). In our daily life, there are diverse circumstances that influence critical effect and change dynamically in accordance with time and environments. Therefore, an innovative approach can be effective for exploiting in advance systems against various environment factors such as radiation, temperature, and atmosphere, which have multifaceted impacts on human health, natural ecosystems, and electronic devices. Although most of the critically harmful radiation can be blocked by the atmospheric ecosystem, various forms of sunlight are essential and either benefit or harm the living organisms depending on their energy and intensity, positioning the importance of considering cumulative dose from temporally intensive or prolonged weak exposures (17–26).

To enable electronic hardware to recognize radiation dose mechanisms, it is crucial to establish criteria that differentiate between the beneficial and harmful radiation levels. Therefore, numerous research for cognitive computing has been conducted to mimic the functions

of sensory receptors, particularly the nociceptors for risk signal transmission through a threshold behavioral command (27–32). Although previous advances are noteworthy, most of the research focuses on emulating the basic biological behaviors and accessing information for in-memory, in-computing, and in-sensing applications (33–35). The appropriate responses are mostly performed with on-demand approaches, still lacking in self-control, which enables perceiving emergency and providing corresponding adaptive activities. Most of the developed radiation sensory systems lack in performing the ideal neuromorphic functions including the autonomous risk recognition and latency-strict response to intensive and cumulative hazardous radiation exposure. Previous studies have primarily used bulky, rigid chip-based elements and complex wiring, which hinders the integration of advanced biomimetic electronics. Consequently, fundamental functions of risk recognition and transducing noxious information to processing or controlling parts are often realized via incomplete signal chains and separate device components, such as program-encoded chip-based microprocessors, forming on-demand system architectures. (10, 36–40).

Herein, we implemented a monolithically integrated biological melanogenesis-inspired neuromorphic device for biomimetic protection against harmful levels of ultraviolet (UV) radiation, especially UVA (315 to 400 nm). Among several UV rays, UVA has been selected because it covers most of the UV light (more than 95%) (23) that is not absorbed by the ozone layer. Specifically, in this experiment, a 365-nm light-emitting diode, which is the middle point of the UVA spectrum, was used to represent the impact of UVA, responsible for long-term effects on human skin. Melanogenesis, the biological process of melanin production in response to UV exposure, shares substantial similarities with stimulus-response mechanisms. Inspired by this natural protective mechanism, we integrated neuromorphic engineering to develop a system that mimics the skin's tanning response, monitors UV radiation levels, and provides adaptive protection through efficient, real-time responses. By mimicking the complete neuromorphic functionality, the dedicated thin-film electronics for biomimetic radiation shielding can be developed with neuromorphic optoelectronic circuitry including thin-film devices for photovoltaic nociceptor

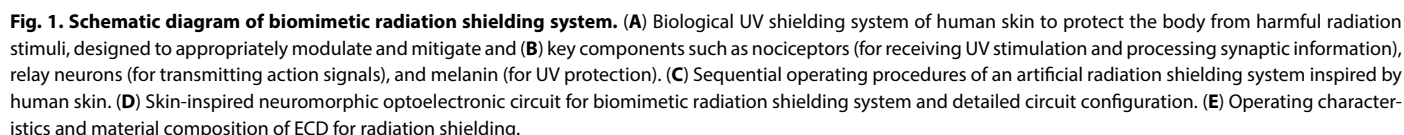
¹Department of Intelligent Semiconductor Engineering, Chung-Ang University, Seoul 06974, Republic of Korea. ²Department of Advanced Components and Materials Engineering, Suncheon National University, Suncheon 57922, Republic of Korea. ³Department of Semiconductor Science, Dongguk University, Seoul 04620, Republic of Korea. ⁴School of Chemical Engineering, Pusan National University, Busan 46241, Republic of Korea. ⁵Electrical Engineering Division, Department of Engineering, University of Cambridge, 9 JJ Thomson Avenue, Cambridge CB3 0FA, UK. ⁶School of Advanced Materials Science and Engineering, Sungkyunkwan University, Suwon 16419, Republic of Korea.

*Corresponding author. Email: skpark@cau.ac.kr (S.K.P.); yhkim76@skku.edu (Y.-H.K.)

†These authors contributed equally to this work.

activation can be provided within 49 to 116 s in the range of 90 to 30 W m⁻², respectively, demonstrating the self-adaptable response of the system corresponding to UV exposure. The sensitivity and response time can be autonomously modulated with UV exposure conditions, and in addition, they can be controlled by the bias supplied to the system, indicating a more rapid response time of 16.9 s under a UV irradiation of 5 W m⁻². The results reported here imply that the explored neuromorphic device allows a general route to realize high-performance and extremely dedicated autonomous sensory devices with marginal power consumption and process complexity, offering compatibility with standard CMOS processing and large-scaled compact device applications.

Skin-inspired neuromorphic optoelectronic circuit

Downloaded from <https://www.science.org> at Chungang University on October 20, 2024

located in the dermis, monitor the UV radiation. For tolerable UV radiation such as temporal or weak UV exposure condition that causes negligible radiation damages, the nociceptors merely respond to UV and subsequent actions are not triggered. In contrast, as shown in Fig. 1C, when the UV radiation is repeated or intensified to a certain level that exceeds the tolerance limit, risk recognition and subsequent blocking responses are initiated. To implement such a skin-inspired UV shielding system, neuromorphic optoelectronic circuitry that mimics the radiation protection mechanism of the human body is designed as shown in Fig. 1D. The biomimetic UV shielding system consists of a photovoltaic nociceptor, a DT, and an ECD, which respectively represent the artificial nociceptor, artificial relay neuron, and artificial melanin. At first, considering the primary roles of artificial nociceptors including the perception of UV radiation and conversion into electric signals, the artificial nociceptor was designed in a photovoltaic voltage divider structure, consisting of a neuromorphic UV sensor (NUS) and a UV-blind load transistor (LT). The NUS and LT were fabricated using InGaZnO thin-film transistors (IGZO TFTs) with UV transparent and UV shielding (reflective) top gate (TG) electrodes, respectively. The NUS perceives the cumulative irradiation of UV light, while the LT determines the autonomous bias supply to the gate node of DT, depending on the resistance ratio of NUS and LT. When the cumulated bias is below a threshold, no subsequent signal is transmitted in the system, as the DT is at off-state. In contrast, when above the threshold, the DT is at on-state, and supply a postsynaptic current (PSC) signal to the ECD in the system. As shown in Fig. 1E, when sufficient PSC and a bias (V_{ECD}) that exceeds the onset voltage of ECD (V_{onset}) are transmitted to the ECD, the ECD undergoes progressive electrochemical coloration, blocking the UV penetration. The colorized state or the pigmentation of ECD can be retained for certain durations, owing to the retention behavior of the artificial nociceptor. The ECD is fabricated using diallyl viologen (DAV) as an active coloring species and ionic liquid as an ion provider, enabling the response capability subject to the supplied voltage corresponding to the PSC signal of the DT. In detail, the coloration occurs due to the reduction of viologen dicationic state (V^{2+}) to radical state (V^{+}), leading to strong absorption in the visible light and UV spectra (43, 44). Under tolerable UV intensity and exposure time, the ECD maintains at a high transmittance state, whereas excessive UV dose above a certain critical level initiates the coloration process, blocking the UV transmission. To summarize, by using a neuromorphic optoelectronic circuitry that emulates the radiation protection mechanism of human skin, autonomous risk recognition and self-adaptive UV shielding were enabled.

Device configuration and optoelectronic properties of the artificial nociceptor

Figure 2A shows the schematic structure and cross-sectional transmission electron microscopy (TEM) images of the photovoltaic artificial nociceptor. In addition, figs. S1 and S2 exhibit the structural and elemental mapping analysis data for NUS and LT, respectively. In the cases of NUS and LT, IGZO TFTs with TG configuration were used. For the UV-blind LT, UV-reflective Cr/Ag (10.5/70.5 nm thick) was used as the gate electrode due to its high reflectance for UVA (45), preventing UV absorption in the IGZO channel (Fig. 2B). In contrast, for the UV-sensitive NUS, the UV transparent Indium

Tin Oxide (ITO) gate electrode (150 nm thick) was used to allow sufficient UV absorption in the IGZO channel. Note that due to the wide bandgap (~ 3.73 eV) of the IGZO semiconductor, as shown in Fig. 2C, the NUS can indicate a larger response to UV light compared to visible light. The photoresponse characteristics of NUS and LT under light irradiation were investigated using monochromatic light sources with peak wavelengths of 635 nm (R), 519 nm (G), 454 nm (B), and 365 nm (UV) (light intensity = 30 W m^{-2}). As shown in Fig. 2D, the LT exhibited negligible or substantially low photocurrent generation under all lighting conditions due to the light-shielding effect from the Cr/Ag TG electrode. Comparably, the NUS demonstrated a large UV response (Fig. 2E), attributed to the efficient UV penetration through the transparent ITO TG electrode and subsequent photo-carrier generation in the IGZO channel. Meanwhile, the NUS showed negligible photoresponse to visible light, an essential characteristic for selective detection and blocking of UV light.

In conventional photosensors, photo-generated current is not maintained in the absence of light illumination and rapidly decays, showing the lack of memory functions. However, as illustrated in Fig. 2F, the NUS demonstrates a memory function wherein the drain current level that increased upon 50 pulses of UV irradiation is maintained for a long duration even in the absence of light illumination. In addition, a cumulative update of conductance state is also observed. Such nonvolatile cumulative updating behavior is possibly due to the persistent photoconductivity (PPC) of IGZO, which is originated from the photo-induced ionization of oxygen vacancies (V_{O}) in IGZO (46, 47). First, the presence of V_{O} in IGZO was confirmed by x-ray photoelectron spectroscopy, showing an area ratio of 17.34% in the O 1s spectra (fig. S3) (48–50). Under UV exposure, excessive electrons are generated by the photoionization of V_{O} defects and increase the conductance state of IGZO and the drain current level of NUS (Fig. 2G, under first UV exposure). Even after the termination of UV irradiation, the increased conductance state can be maintained for a certain duration, because the neutralization process of ionized V_{O} is a nonspontaneous process that requires activation energy (Fig. 2G, after the end of the first UV exposure) (47). When subsequent UV irradiation is followed before the complete neutralization of ionized V_{O} , the conductance state of IGZO will continue to increase due to the accumulation of photo-generated electrons (Fig. 2G, under second UV exposure and termination). Based on these features of the IGZO semiconductor, light exposure history-based conductance update is possible in the NUS. Figure 2 (H to J) shows the photoresponse characteristics of NUS under different duration, frequency, and number of UV light pulses. It is observed that more frequent and longer exposure to UV light resulted in larger increase of drain current and longer retention behavior, which can be used for the self-adaptive risk-recognition system, reflecting the exposure history of UV irradiation.

Operation principle of neuromorphic optoelectronic circuitry and the influence of repetitive UV stimulation

The operation of neuromorphic optoelectronic circuitry under repeated UV irradiation is investigated in more detail. As discussed, the neuromorphic optoelectronic circuitry consists of a photovoltaic nociceptor, a DT, and an ECD, which act as an artificial nociceptor, artificial relay neuron, and artificial melanin, respectively

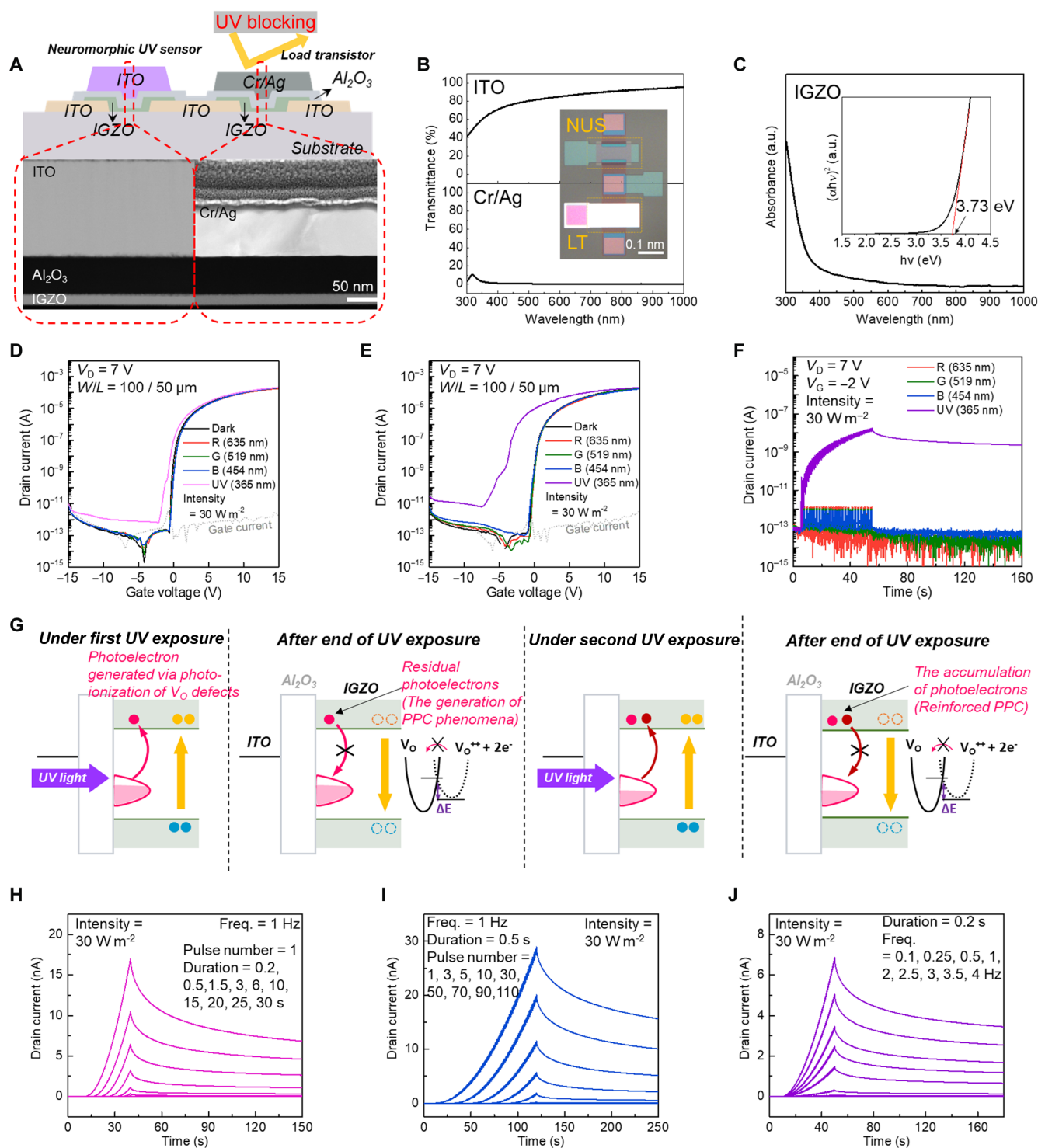


Fig. 2. Device configuration and optoelectronic properties of NUS and LT in photovoltaic nociceptor. (A) Device structure and cross-sectional TEM images of NUS with ITO TG electrode and LT with Cr/Ag TG electrode. (B) Optical transmittance spectra of ITO and Cr/Ag TG electrodes. (C) Light absorption characteristics of the IGZO semiconductor. The inset shows the corresponding Tauc plot. Photoresponse characteristics of (D) LT and (E) NUS under dark and light illumination conditions [red (635 nm), green (519 nm), blue (454 nm), and UV (365 nm)]. (F) Neuromorphic photosensing characteristics and (G) operation mechanism of NUS under UV stimulation (light pulse condition: wavelength of 365 nm, frequency of 1 Hz, duration of 0.5 s, pulse number of 50, and intensity of 30 W m^{-2}). Photosensing characteristics of NUS depending on various UV stimulation conditions: (H) exposure duration (light pulse condition: intensity of 30 W m^{-2} , duration of 0.2 to 30 s, and pulse number of 1), (I) exposure number (light pulse condition: intensity of 30 W m^{-2} , frequency of 1 Hz, duration of 0.5 s, and pulse number of 1 to 110), and (J) exposure frequency (light pulse condition: intensity of 30 W m^{-2} , frequency of 0.1 to 4 Hz, duration of 0.2 s, and total exposure time of 40.2 s). V_D and V_G were fixed to 7 and -2 V , respectively.

(Fig. 3, A and B). The photovoltaic nociceptor is composed of UV-sensitive NUS and UV-blind LT, which are interconnected with the form of a voltage divider, mimicking the essential functions of biological nociceptor including the reception of repeated UV irradiation and photovoltaic signal conversion. The DT transmits appropriate action signal to ECD according to the accumulated voltage signal (V_N) received from the photovoltaic nociceptor (Fig. 3B), while monitoring the risk recognition by the PSC value of the DT (fig. S4). In addition, when the V_{ECD} applied between the two electrodes of ECD is gradually increased, owing to the accumulated UV stimulation, the ECD undergoes progressive electrochemical coloration (pigmentation), leading to a decrease in UV transmittance and activation of UV shielding behaviors. In the initial state without UV stimulation, the V_N of the photovoltaic nociceptor, the PSC of the DT, and the V_{ECD} of the ECD exhibit values close to zero (Fig. 3A). The V_N at the node of photovoltaic nociceptor and the gate of DT is defined by the following equation

$$V_N = V_{DD} \cdot R_{LT} / (R_{NUS} + R_{LT}) \quad (1)$$

where R_{NUS} and R_{LT} represent the electrical resistance of NUS and LT, respectively, and V_{DD} is the supply bias applied to the photovoltaic nociceptor. In this circuit, the initial R_{NUS} and R_{LT} values can be modulated by the gate-bias conditions of NUS and LT. For example, when the initial R_{NUS} is much larger than the initial R_{LT} , the V_N value approaches 0 V (Fig. 3A). In our case, the gate bias of NUS and LT was set to -2 V ($V_{G,NUS} = -2$ V) and 0 V ($V_{G,LT} = 0$ V), respectively. As a result, the NUS is highly resistive (initial $R_{NUS} \sim 10^{13}$ ohms), compared to the LT (initial $R_{LT} \sim 10^{11}$ ohms). This is because the electron concentration in the IGZO channel layer of NUS is greatly reduced with the applied negative gate bias (Fig. 3C, NUS and NT). Therefore, the V_N of the photovoltaic nociceptor shows near-zero value and no subsequent signal supplies (Fig. 3C, DT off), resulting in a low PSC of <100 pA and a near-zero V_{ECD} . In contrast, when UV light is irradiated, as described in Fig. 3D, the NUS gradually becomes conductive owing to the photo-generated electrons. Furthermore, when continuous or repeated UV stimulation is provided, the R_{NUS} progressively decreases due to the gradual increase of photoelectrons by the PPC effect (Fig. 3E, under UV stimulation). Specifically, as shown in Fig. 3 (B and E), with repeated UV exposure, the R_{NUS} can decrease much lower than the R_{LT} , leading to a gradual increase of the V_N (Fig. 3F, under UV stimulation). The updated V_N is then supplied to the gate of DT, while reducing the resistance (R_{DT}) and an increase of PSC as indicated in Fig. 3G. In particular, when the updated V_N exceeds a critical voltage (V_C), a high PSC and sufficient V_{ECD} ($\geq V_{onset}$) are provided to the ECD (Fig. 3H, under UV stimulation) and then it can induce electrochemical coloration of ECD as well as the reduction of $T_{UV,ECD}$.

Figure 3 (I to L) shows the variation V_N under various UV irradiation conditions. As exhibited in Fig. 3I and fig. S5, it is noted that the update rate of V_N is varied depending on the frequency of UV exposure. Because the amount of absorbed UV light is typically calculated by dose (light intensity $\times$ exposed time) ($\text{W} \cdot \text{m}^{-2} \cdot \text{s}$), the frequency can be one of the crucial factors. Considering the UV index, we used various intensities of light for our experiments to determine the critical level requiring protection (fig. S6) (51). As the frequency increases, the update rate of V_N tends to increase along with the shortened time required for the V_N to reach V_C . Moreover, when the frequency was lower than 0.5 Hz, the V_N rarely reached V_C within a given exposure time (200 s). Under continuous and repetitive

stimulation (1 Hz) of UV light, V_N increases rapidly and then exceeds V_C ($V_C = 1.5$ V) after 68 and 120 s, respectively, from the initial exposure. This indicates that continuous UV exposure shorter than 68 s will not trigger certain subsequent actions. However, when continuous UV exposure is longer than 68 s, V_N exceeds V_C , and the risk recognition and ECD pigmentation are enabled. Furthermore, it is also important to note that the updated V_N can be retained even after the termination of UV irradiation due to the memory-like behavior of NUS. Correspondingly, the radiation shielding function through the pigmentation of ECD will be maintained when the stimulation is eliminated, which is almost identical to the biological melanin-based UV blocking mechanism. In the biomimetic radiation shielding system, the intensity of radiation stimuli also had a considerable influence on photoresponse behaviors of the system. As shown in Fig. 3J, under stronger UV intensity, the update rate of V_N is accelerated, reducing the time (τ_{V_N,V_C}) required to reach V_C . In particular, V_N reached V_C after 51 s when exposed to a UV stimulation of 90 W m^{-2} , while it required 120 s when the intensity was 30 W m^{-2} . These results imply that with a larger dose of incident UV stimuli, the onset of subsequent pigmentation process can be accelerated.

Meanwhile, the sensitivity of photovoltaic nociceptor or the increasing rate of V_N under UV stimulation can also be modulated by the elaborate control of R_{LT} , which aligns with the gate bias of LT. When a larger negative gate bias is applied, the R_{LT} can be increased along with the sensitivity of the photovoltaic nociceptor. As a result, a higher rate of V_N updating is enabled with identical UV stimulation. In contrast, applying a large positive gate bias decreases the R_{LT} and causes the photovoltaic nociceptor to be less sensitive, resulting in slower updating of V_N . As demonstrated in Fig. 3K, when positive or zero gate bias is supplied to LT, the photovoltaic nociceptor fails to provide a meaningful V_N exceeding V_C within 200 s (intensity of 5 W m^{-2}). On the other hand, as exhibited in Fig. 3L and fig. S7, when a negative gate bias is applied, higher sensitivity can be obtained and therefore the time required to reach V_C is substantially decreased with the identical UV light intensity. For instance, with an LT gate bias of -0.75 V, V_N exceeded V_C after around 16.9 s. These findings clearly validate that the gate bias of LT can be used to control the sensitivity of the photovoltaic nociceptor, providing the capability to adjust the threshold UV exposure under specific environment conditions. The importance of controlling the degree of UV shielding is further needed by various factors, such as individual differences in skin tones, pupil size, and geographic latitude, which affect the amount of UV light required. As described, the DT in neuromorphic optoelectronic circuit transmits PSC to the ECD according to V_N level. When a large V_N is supplied from high frequent or stronger UV light exposure, a substantial PSC can be provided to the ECD, allowing risk recognition and ECD pigmentation depending on the exposure history of UV stimulation (Fig. 3, M and N).

Biomimetic UV shielding electronic skin using neuromorphic optoelectronic circuits

To validate the efficacy of the monolithically integrated neuromorphic sensory platform, a multicell combined with optoelectronic circuitry and EC devices were implemented on a $10\text{-}\mu\text{m}$ -thick colorless polyimide (CPI) substrate. Here, we investigate the emulation of biological melanogenesis in those fabricated devices by using various UV environmental conditions. Figure 4A illustrates the structure of ECD used as the artificial melanin for UV blocking. The ECD comprises EC ion gel sandwiched between top electrode (TE) and bottom

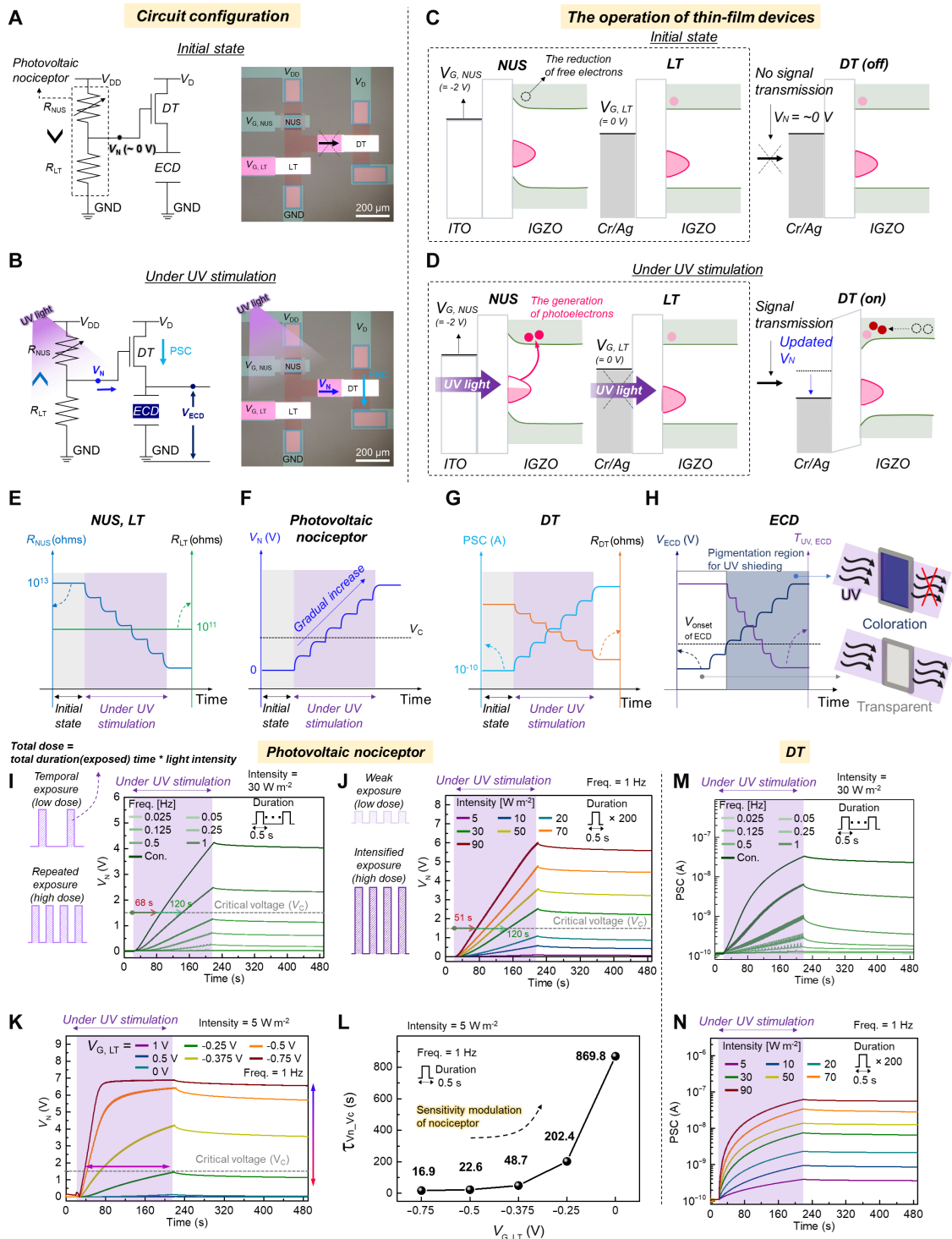


Fig. 3. Operation principle of neuromorphic optoelectronic circuitry and the influence of repetitive UV stimulation. Circuit schematic and working mechanism of neuromorphic optoelectronic circuitry: (A) in initial state and (B) under UV stimulation. The individual operation states of thin-film devices (NUS, LT, and DT) present on neuromorphic optoelectronic circuitry: (C) in initial state and (D) under UV stimulation. Changes in optoelectronic properties of thin film unit devices due to UV stimulation: (E) the resistances of NUS (R_{NUS}) and LT (R_{LT}), (F) the V_N of photovoltaic nociceptor, (G) the PSC and resistance of DT (R_{DT}), and (H) V_{ECD} and $T_{UV,ECD}$ of ECD. The variation of V_N provided from node of photovoltaic nociceptor under various UV stimulation conditions: (I) exposure frequency and (J) exposure intensity. V_{DD} , $V_{G,NUS}$, and $V_{G,LT}$ were fixed to 7, -2, and 0 V, respectively. (K) Sensitivity modulation of photovoltaic nociceptor via gate-bias control in LT. $V_{G,LT}$ was varied from 1 to -0.75 V. The $V_{G,NUS}$ and V_{DD} were fixed at -2 and 7 V, respectively. (L) The variation of τ_{VN,V_C} under UV stimulation via gate-bias control of LT. PSC changes in DT under different UV stimulation conditions: (M) exposure frequency and (N) exposure intensity. V_{DD} , $V_{G,NUS}$, $V_{G,LT}$, and V_D were fixed to 7, -2, 0, and 7 V, respectively.



electrode (BE). The EC ion gel contains electrochromic chromophores for bluish coloration in a gel-type electrolyte platform. The color can be modulated through an electrochemical coloration process depending on the electrical bias (V_{ECD}) supplied between the two electrodes (Fig. 4B). The onset voltage for the bluish coloration was 0.7 V, and the transmittance decreased with increasing V_{ECD} . The cyclic voltammetry analysis indicates that the electrochemical redox reaction related to the bluish coloration started at 0.7 V and gradually activated with increasing V_{ECD} (fig. S8). In addition, the blue ECD shows the most power-efficient operation characteristic with a lower driving voltage ($V_{\text{ECD}} = 0.7$ V), compared to the red and green ECD ($V_{\text{ECD}} = 1.1$ V). In addition, it showed the most stable dynamic operating characteristics, as shown in fig. S9. Furthermore, as shown in fig. S10, the degree of UVA transmittance [wavelength (λ) of 300 to 400 nm] through the ECD is substantially suppressed with the coloration. Especially at a wavelength of 365 nm, UV transmittance was markedly reduced from 64% ($V_{\text{ECD}} = 0$ V) to 3% ($V_{\text{ECD}} \geq 1.0$ V), accompanied by a change occurring without critical heat emission (Fig. 4C and fig. S11). This observation clearly demonstrates that efficient UV blocking can be achieved through the electrochemical coloration of ECD. Figure 4D shows the monolithically integrated UV shielding electronic skin using neuromorphic circuit on a CPI substrate. Briefly, the CPI solution was first spun on a carrier glass substrate, and an Al_2O_3 thin film was deposited as a buffer layer. After the fabrication of a photovoltaic nociceptor and DT, an ITO BE for ECD was deposited. Then, the spacers and pillars based on the SU-8 photoresist were formed at spacer and active regions to contain EC ion gel and to avoid uneven coloration (Fig. 4E and figs. S12 and S13) (52, 53). Last, after detaching the CPI substrate from the carrier glass, EC ion gel deposition by drop casting and the ITO TE bonding process were carried out. Figure 4F shows a prototype of the monolithically integrated neuromorphic device attached on the skin.

Figure 4 (G to K) shows the schematic layout and operation principles of the UV radiation shielding system. This neuromorphic sensory system consists of an optoelectronic circuit with three monolithically connected cells. As shown in Fig. 4G, to reduce the number of contact pads, the electrodes in each cell, such as $V_{\text{G,NUS}}$, $V_{\text{G,LT}}$, GND (ground), V_{DD} , and V_{D} , were interconnected, sharing with other cells. Furthermore, DT and ECD were connected in series, allowing common current signal along the V_{D} line. Therefore, the voltage supplied to the ECD (V_{ECD}) is proportionally modulated with the PSC value. In addition, with repeated exposure of UV radiation (intensity of 30 W m^{-2}), the V_{ECD} increased progressively from 0 to 0.7 V, exceeding the V_{onset} within 116 s (Fig. 4H). Subsequently, the electrochemical coloration and darkening [UV shielding efficiency ($100 - T_{\text{UV,ECD}} = 57\%$) of ECD can be triggered consecutively in response to the cumulative UV radiation as depicted in Fig. 4J]. Furthermore, the UV blocking states caused by the repeated UV stimulation can be maintained because of the memory-like behaviors of NUS (fig. S14). As shown in fig. S15, it is confirmed that the neuromorphic optoelectronic circuitry reversibly returns to the initial state by applying an appropriate bias to the gate of the NUS. Figure 4I shows the increasing rate of V_{ECD} depending on the irradiated UV intensity. Despite the identical exposure time, the V_{ECD} remains below the V_{onset} when low-intensity UV stimulation was applied ($<30 \text{ W m}^{-2}$). In contrast, with high-intensity UV stimulation (90 W m^{-2}), the increasing rate of V_{ECD} is accelerated, leading to faster (49 s) and stronger pigmentation [UV shielding efficiency ($100 - T_{\text{UV,ECD}} = 97\%$) of ECD]. Therefore, in the case of

more risky UV irradiation environments (with higher UV intensity), the responsive activities of the neuromorphic electronic skin can be facilitated much faster and more distinctively, as shown in Fig. 4K. Furthermore, in addition to neuromorphic electronic skin, as shown in fig. S16, various wearable neuromorphic applications such as smart glasses and smart farm using neuromorphic electronics with environmentally adaptive UV shielding were also further explored.

DISCUSSION

As highlighted, previous research of neuromorphic sensors primarily focused on emulating simple functionalities of synapses and neurons. At this stage, we advocate for a shift in research focus toward more effective and realistic functionalities for harmful environments, using a simple and compact device architecture that mimics relevant biological processes. This study presents a photovoltaic neuromorphic thin-film system with autonomous radiation shielding capability, implemented by monolithically integrated transparent flexible optoelectronic devices, and piling the entire signal chain into the devices. Inspired by the human biological system, the neuromorphic devices comprised a photovoltaic nociceptor, a DT, and an ECD, representing the artificial nociceptor, relay neuron, and melanin, respectively. It successfully emulated the biological melanogenesis and neural responses to repeated UV exposure. Consequently, autonomous risk perception under various environmental UV conditions and the radiation shielding actions in response to stimulation history were provided sequentially. The approach suggested here, featuring monolithically integrated devices and biomimetic neural processing, offers a pathway for a substantial advancement in a radiation shielding technology for prolonged exposure, extending its application to a wide range of fields such as wearable technology, medical health care, and space exploration.

MATERIALS AND METHODS

Fabrication of NUV, LT, and DT for neuromorphic circuit

To manufacture a transparent flexible substrate for UV shielding electronics, a CPI solution was spin coated onto a glass carrier substrate (Eagle XG, Corning) and thermally annealed at 300°C for 60 min. Next, a 55-nm-thick Al_2O_3 buffer layer was deposited on the 10- μm -thick CPI substrate through an atomic layer deposition (ALD) process at 150°C using trimethylaluminum as aluminum precursor and water as oxygen precursor. Next, all IGZO transistors, including the NUV, LT, and DT, were simultaneously manufactured with a TG and bottom-contact device structure on the Al_2O_3 buffer layer. As source and drain electrodes, a 75-nm-thick ITO layer was deposited using radio frequency (RF) sputtering and patterned through a conventional lift-off process. Then, as a semiconducting channel, a 17-nm-thick IGZO layer was deposited via RF sputtering using an InGaZnO target (In:Ga:Zn molar ratio of 1:1:1), and then thermally annealed at 300°C for 10 min. The IGZO layer was patterned through conventional photolithography and wet etching processes. Next, as gate dielectric, a 55-nm-thick Al_2O_3 layer was deposited on top of the patterned IGZO layer via the ALD process at 150°C . Then, it was patterned by conventional photolithography and wet etching processes to form contact holes. Thereafter, as a UV reflective TG electrode for LT and DT, a Cr/Ag layer with a film thickness of 10 nm/70 nm was deposited by thermal evaporation and patterned through a conventional lift-off process. Ag and Cr were used

for the UVA-blind layers due to the high reflectance of UVA and the oxidation-preventing properties of the Ag layer, respectively. On the other hand, as a transparent TG electrode for NUS, a 150-nm-thick ITO layer was deposited via RF sputtering and then patterned through a conventional lift-off process. Here, the channel width/length of all transistor devices were 100 μm /50 μm .

Fabrication of ECD and monolithic integration for neuromorphic circuit

An electrochromic active species, DAV, intended for an artificial electrochromic melanin device, was synthesized using a specific process (54). Initially, 2 g of 4,4'-bipyridine (2.80 mmol) and 3.87 g of allyl bromide (32.01 mmol) were combined in acetonitrile. This mixture was stirred continuously at 90°C under a nitrogen atmosphere for 24 hours. Upon cooling, the formed pale-yellow solid was filtered out and subsequently washed with diethyl ether and acetonitrile, repeated three times. Last, the solid was collected and allowed to dry at room temperature. The yield of the product was 1.82 g, constituting a 91% yield. The prepared allyl viologen and ammonium hexafluorophosphate (NH_4PF_6) with a 1:3 M quantity were dissolved and stirred in 10 ml of methanol at room temperature for 24 hours. After the reaction, the product was isolated by filtration and washed with cold distilled water repeatedly to remove the excess amount of the reactant and the remaining by-products. The anion-exchanged solid, $[\text{DAV}][\text{PF}_6]_2$, was collected by filtration and dried at room temperature. The UV-curable ion gel solution was prepared by mixing $[\text{DAV}][\text{PF}_6]_2$ (200 mg) as an active species, ferrocene (30 mg) as an anodic species, poly(ethyleneglycol) diacrylate (800 mg) and poly(urethane acrylate) (200 mg) as polymer matrices, 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide (2 g) and bis(trifluoromethane)sulfonimide lithium salt (400 mg) as ionic species, methacrylate polyhedral oligomeric silsesquioxane (50 mg) as a cross-linking additive, and 2-hydroxy-2-methylpropiophenone (600 mg) and diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (3.25 mg) as UV initiators in methyl ethyl ketone. Next, to fabricate an artificial melanin device in the same plane where the photovoltaic nociceptor and DT are located, the SU-8 photoresist pattern (50 μm thick) was formed as a container and spacer for the ion gel via conventional photolithography and then thermally cured at 170°C for 10 min. To expand it to a flexible platform, the device formed on PI is detached from the carrier glass. The ion gel solution was injected into the SU-8 frame pattern via drop-casting processing. Then, for the formation of ECD, UV exposure for 30 s was performed by covering the top ITO electrode deposited on a polyethylene terephthalate substrate.

Characterization of the films and devices

The macroscopic and microstructural features of devices were characterized via optical microscope and bright-field TEM images. Optical absorption and transmittance spectra of the IGZO, ITO, Al_2O_3 , and CPI films deposited on the glass substrate were measured using a UV-visible spectrophotometer (UV-Vis; Shimadzu). The chemical bonding states of the IGZO film were analyzed via x-ray photoelectron spectroscopy (XPS; Thermo VG Scientific) through a monochromatic $\text{Al K}\alpha$ (1486.6 eV) x-ray source. The electrical measurements of all devices were evaluated using a semiconductor parameter analyzer (Agilent 4156C, Agilent Technologies) in ambient air at room temperature under dark and illuminated conditions. As light sources, several light-emitting diodes with peak wavelengths centered at 365 nm

(UV), 454 nm (blue), 519 nm (green), and 635 nm (red) were used, which were controlled by a function generator (AFG31000, Keithley).

Supplementary Materials

This PDF file includes:

Figs. S1 to S16

REFERENCES AND NOTES

1. S. Kim, S. Kim, D. H. Ho, D. G. Roe, Y. J. Choi, M. J. Kim, U. J. Kim, M. L. Le, J. Kim, S. H. Kim, J. H. Cho, Neurorobotic approaches to emulate human motor control with the integration of artificial synapse. *Sci. Adv.* **8**, eabo3326 (2022).
2. D. Ham, H. Park, S. Hwang, K. Kim, Neuromorphic electronics based on copying and pasting the brain. *Nat. Electron.* **4**, 635–644 (2021).
3. X. Yu, T. J. Marks, A. Facchetti, Metal oxides for optoelectronic applications. *Nat. Mater.* **15**, 383–396 (2016).
4. Y. Choi, S. Oh, C. Qian, J. H. Park, J. H. Cho, Vertical organic synapse expandable to 3D crossbar array. *Nat. Commun.* **11**, 4595 (2020).
5. H. Guo, X. Pu, J. Chen, Y. Meng, M. H. Yeh, G. Liu, Q. Tang, B. Chen, D. Liu, S. Qi, C. Wu, C. Hu, J. Wang, Z. L. Wang, A highly sensitive, self-powered triboelectric auditory sensor for social robotics and hearing aids. *Sci. Robot.* **3**, eaat2516 (2018).
6. Y. Liu, E. Li, X. Wang, Q. Chen, Y. Zhou, Y. Hu, G. Chen, H. Chen, T. Guo, Self-powered artificial auditory pathway for intelligent neuromorphic computing and sound detection. *Nano Energy* **78**, 105403 (2020).
7. S.-W. Lee, M. Kang, J.-K. Han, S.-Y. Yun, I. Park, Y.-K. Choi, An artificial olfactory sensory neuron for selective gas detection with in-sensor computing. *Device* **1**, 100063 (2023).
8. N. Imam, T. A. Cleland, Rapid online learning and robust recall in a neuromorphic olfactory circuit. *Nat. Mach. Intell.* **2**, 181–191 (2020).
9. T. Someya, T. Sekitani, S. Iba, Y. Kato, H. Kawaguchi, T. Sakurai, A large-area, flexible pressure sensor matrix with organic field-effect transistors for artificial skin applications. *Proc. Natl. Acad. Sci. U.S.A.* **101**, 9966–9970 (2004).
10. F. Sun, Q. Lu, M. Hao, Y. Wu, Y. Li, L. Liu, L. Li, Y. Wang, T. Zhang, An artificial neuromorphic somatosensory system with spatio-temporal tactile perception and feedback functions. *Npj Flex. Electron.* **6**, 72 (2022).
11. T. Birkoben, H. Winterfeld, S. Fichtner, A. Petraru, H. Kohlstedt, A spiking and adapting tactile sensor for neuromorphic applications. *Sci. Rep.* **10**, 17260 (2020).
12. C. Choi, J. Leem, M. S. Kim, A. Taqieddin, C. Cho, K. W. Cho, G. J. Lee, H. Seung, H. J. Bae, Y. M. Song, T. Hyeon, N. R. Aluru, S. W. Nam, D. H. Kim, Curved neuromorphic image sensor array using a MoS_2 -organic heterostructure inspired by the human visual recognition system. *Nat. Commun.* **11**, 5934 (2020).
13. Q. B. Zhu, B. Li, D. D. Yang, C. Liu, S. Feng, M. L. Chen, Y. Sun, Y. N. Tian, X. Su, X. M. Wang, S. Qiu, Q. W. Li, X. M. Li, H. B. Zeng, H. M. Cheng, D. M. Sun, A flexible ultrasensitive optoelectronic sensor array for neuromorphic vision systems. *Nat. Commun.* **12**, 1798 (2021).
14. C. Jo, J. Kim, J. Y. Kwak, S. M. Kwon, J. B. Park, J. Kim, G. S. Park, M. G. Kim, Y. H. Kim, S. K. Park, Retina-inspired color-cognitive learning via chromatically controllable mixed quantum dot synaptic transistor arrays. *Adv. Mater.* **34**, 2108979 (2022).
15. S. M. Kwon, S. W. Cho, M. Kim, J. S. Heo, Y. H. Kim, S. K. Park, Environment-adaptable artificial visual perception behaviors using a light-adjustable optoelectronic neuromorphic device array. *Adv. Mater.* **31**, 1906433 (2019).
16. S. M. Kwon, J. Y. Kwak, S. Song, J. Kim, C. Jo, S. S. Cho, S. J. Nam, J. Kim, G. S. Park, Y. H. Kim, S. K. Park, Large-area pixelized optoelectronic neuromorphic devices with multispectral light-modulated bidirectional synaptic circuits. *Adv. Mater.* **33**, 2105017 (2021).
17. H. J. Lee, S. Yoo, J. K. Hong, J. S. Ahn, E. Lee, H. Moon, S. Koo, T. Kim, J. Park, I. Y. Yoon, The effect of proto-type wearable light-emitting devices on serum 25-hydroxyvitamin D levels in healthy adults: A 4-week randomized controlled trial. *Eur. J. Clin. Nutr.* **77**, 342–347 (2023).
18. W. Zou, A. González, D. Jampaiah, R. Ramanathan, M. Taha, S. Walia, S. Sriram, M. Bhaskaran, J. M. Dominguez-Vera, V. Bansal, Skin color-specific and spectrally-selective naked-eye dosimetry of UVA, B and C radiations. *Nat. Commun.* **9**, 3743 (2018).
19. H. Tsai, F. Liu, S. Shrestha, K. Fernando, S. Tretiak, B. Scott, D. T. Vo, J. Strzalka, W. Nie, A sensitive and robust thin-film x-ray detector using 2D layered perovskite diodes. *Sci. Adv.* **6**, eaay0815 (2020).
20. A. R. Young, Acute effects of UVR on human eyes and skin. *Prog. Biophys. Mol. Biol.* **92**, 80–85 (2006).
21. Q. Duan, T. Zhang, C. Liu, R. Yuan, G. Li, P. Jun Tiw, K. Yang, C. Ge, Y. Yang, R. Huang, Artificial multisensory neurons with fused haptic and temperature perception for multimodal in-sensor computing. *Adv. Intell. Syst.* **4**, 2200039 (2022).
22. B. Park, D. Ho, G. Kwon, D. Kim, S. Y. Seo, C. Kim, M. G. Kim, Solution-processed rad-hard amorphous metal-oxide thin-film transistors. *Adv. Funct. Mater.* **28**, 1802717 (2018).

23. A. Q. Khan, J. B. Travers, M. G. Kemp, Roles of UVA radiation and DNA damage responses in melanoma pathogenesis. *Environ. Mol. Mutagen.* **59**, 438–460 (2018).
24. D. L. Narayanan, R. N. Saladi, J. L. Fox, Ultraviolet radiation and skin cancer. *Int. J. Dermatol.* **49**, 978–986 (2010).
25. G. J. Fisher, Z. Wang, S. C. Datta, J. Varani, S. Kang, J. J. Voorhees, Pathophysiology of premature skin aging induced by ultraviolet light. *N. Engl. J. Med.* **337**, 1419–1429 (1997).
26. I. V. Ivanov, T. Mappes, P. Schaupp, C. Lappe, S. Wahl, Ultraviolet radiation oxidative stress affects eye health. *J. Biophotonics* **11**, e201700377 (2018).
27. M. Kumar, H. S. Kim, J. Kim, A highly transparent artificial photonic nociceptor. *Adv. Mater.* **31**, 1900021 (2019).
28. A. E. Dubin, A. Patapoutian, A. E. Dubin, A. Patapoutian, Nociceptors: The sensors of the pain pathway. *J. Clin. Invest.* **120**, 3760–3772 (2010).
29. V. N. Nikolenko, E. M. Shelomentseva, M. M. Tsvetkova, E. I. Abdeeva, D. B. Giller, J. V. Babayeva, E. E. Achkasov, L. V. Gavryushova, M. Y. Sinelnikov, Nociceptors: Their role in body's defenses, tissue specific variations and anatomical update. *J. Pain Res.* **15**, 867–877 (2022).
30. G. Feng, J. Jiang, Y. Zhao, S. Wang, B. Liu, K. Yin, D. Niu, X. Li, Y. Chen, H. Duan, J. Yang, J. He, Y. Gao, Q. Wan, A sub-10 nm vertical organic/inorganic hybrid transistor for pain-perceptual and sensitization-regulated nociceptor emulation. *Adv. Mater.* **32**, 1906171 (2020).
31. Y. Gong, X. Xing, Z. Lv, J. Chen, P. Xie, Y. Wang, S. Huang, Y. Zhou, S.-T. Han, Ultrasensitive flexible memory phototransistor with detectivity of 1.8×10^{13} Jones for artificial visual nociceptor. *Adv. Intell. Syst.* **4**, 2100257 (2022).
32. X. Deng, S. Q. Wang, Y. X. Liu, N. Zhong, Y. H. He, H. Peng, P. H. Xiang, C. G. Duan, A flexible mott synaptic transistor for nociceptor simulation and neuromorphic computing. *Adv. Funct. Mater.* **31**, 2101099 (2021).
33. T. Jiang, Y. Wang, Y. Zheng, L. Wang, X. He, L. Li, Y. Deng, H. Dong, H. Tian, Y. Geng, L. Xie, Y. Lei, H. Ling, D. Ji, W. Hu, Tetrachromatic vision-inspired neuromorphic sensors with ultraweak ultraviolet detection. *Nat. Commun.* **14**, 2281 (2023).
34. H. L. Park, H. Kim, D. Lim, H. Zhou, Y. H. Kim, Y. Lee, S. Park, T. W. Lee, Retina-inspired carbon nitride-based photonic synapses for selective detection of UV light. *Adv. Mater.* **32**, 1906899 (2020).
35. T. W. Cronin, M. J. Bok, Photoreception and vision in the ultraviolet. *J. Exp. Biol.* **219**, 2790–2801 (2016).
36. S. Kim, Y. Y. Choi, T. Kim, Y. M. Kim, D. H. Ho, Y. J. Choi, D. G. Roe, J. H. Lee, J. Park, J. W. Choi, J. W. Kim, J. H. Park, S. B. Jo, H. C. Moon, S. Jeong, J. H. Cho, A biomimetic ocular prosthesis system: Emulating autonomic pupil and corneal reflections. *Nat. Commun.* **13**, 6760 (2022).
37. X. Shi, W. Liu, Y. Xu, C. Jin, G. Zhang, Y. Shi, H. Huang, J. Sun, J. Yang, Ultraviolet-selective organic phototransistors for low-power skin-inspired nociceptor. *Nano Energy* **110**, 108372 (2023).
38. Y. Lee, J. Young Oh, W. Xu, O. Kim, T. Roy Kim, J. Kang, Y. Kim, D. Son, J. B.-H. Tok, M. Jeong Park, Z. Bao, T.-W. Lee, Stretchable organic optoelectronic sensorimotor synapse. *Sci. Adv.* **4**, eaat7387 (2018).
39. C. Jiang, J. Liu, Y. Ni, S. Qu, L. Liu, Y. Li, L. Yang, W. Xu, Mammalian-brain-inspired neuromorphic motion-cognition nerve achieves cross-modal perceptual enhancement. *Nat. Commun.* **14**, 1344 (2023).
40. Y. Kim, A. Chortos, W. Xu, Y. Liu, J. Y. Oh, D. Son, J. Kang, A. M. Foudeh, C. Zhu, Y. Lee, S. Niu, J. Liu, R. Pfattner, Z. Bao, T.-W. Lee, A bioinspired flexible organic artificial afferent nerve. *Science* **360**, 998–1003 (2018).
41. C. J. Woolf, Q. Ma, Nociceptors-noxious stimulus detectors. *Neuron* **55**, 353–364 (2007).
42. R. D. Beer, Dynamical approaches to cognitive science. *Trends Cogn. Sci.* **4**, 91–99 (2000).
43. H. C. Moon, T. P. Lodge, C. D. Frisbie, Solution processable, electrochromic ion gels for sub-1 V, flexible displays on plastic. *Chem. Mater.* **27**, 1420–1425 (2015).
44. H. C. Moon, C. H. Kim, T. P. Lodge, C. D. Frisbie, Multicolored, low-power, flexible electrochromic devices based on ion gels. *ACS Appl. Mater. Interfaces* **8**, 6252–6260 (2016).
45. P. B. Johnson, R. W. Christy, Optical constant of the noble metals. *Phys. Rev. B* **11**, 4370–4379 (1972).
46. S. Jeon, S. E. Ahn, I. Song, C. J. Kim, U. I. Chung, E. Lee, I. Yoo, A. Nathan, S. Lee, J. Robertson, K. Kim, Gated three-terminal device architecture to eliminate persistent photoconductivity in oxide semiconductor photosensor arrays. *Nat. Mater.* **11**, 301–305 (2012).
47. M. Lee, W. Lee, S. Choi, J. Jo, J. Kim, S. K. Park, Y.-H. Kim, Brain-inspired photonic neuromorphic devices using photodynamic amorphous oxide semiconductors and their persistent photoconductivity. *Adv. Mater.* **29**, 1700951 (2017).
48. S. Yoon, Y. J. Tak, D. H. Yoon, U. H. Choi, J.-S. Park, B. Du Ahn, H. J. Kim, Study of nitrogen high-pressure annealing on InGaZnO thin-film transistors. *ACS Appl. Mater. Interfaces* **6**, 13496–13501 (2014).
49. K. Kim, S. Jeon, W. Lee, J. Jo, J. S. Heo, I. Kim, Y. Kim, S. K. Park, A site-specific charge carrier control in monolithic integrated amorphous oxide semiconductors and circuits with locally induced optical-doping process. *Adv. Funct. Mater.* **29**, 1904770 (2019).
50. J. Chung, Y. J. Tak, W.-G. Kim, B. H. Kang, H. J. Kim, Artificially fabricated subgap states for visible-light absorption in indium–gallium–zinc oxide phototransistor with solution-processed oxide absorption layer. *ACS Appl. Mater. Interfaces* **11**, 38964–38972 (2019).
51. R. M. Lucas, R. E. Neale, S. Madronich, R. L. McKenzie, Are current guidelines for sun protection optimal for health? Exploring the evidence. *Photochem. Photobiol. Sci.* **17**, 1956–1963 (2018).
52. G. K. Pande, J. S. Heo, J. H. Choi, Y. S. Eom, J. Kim, S. K. Park, J. S. Park, RGB-to-black multicolor electrochromic devices enabled with viologen functionalized polyhedral oligomeric silsesquioxanes. *Chem. Eng. J.* **420**, 130446 (2021).
53. S.-M. Lee, S. H. Oh, K. C. Choi, Highly transparent SU-8 photoresist barrier rib for a transparent AC plasma display panel. *J. Display Technol.* **7**, 40–43 (2011).
54. G. K. Pande, D. Y. Kim, F. Sun, R. Pal, J. S. Park, Photocurable allyl viologens exhibiting RGB-to-black electrochromic switching for versatile heat-shielding capability. *Sol. Energy Mater. Sol. Cells* **263**, 112579 (2023).

Acknowledgments

Funding: This work was supported by a National Research Foundation of Korea (NRF) grant funded by the Korean government (MSIP) (no. RS-2024-00347845), the Nano & Material Technology Development Program through the NRF funded by the Ministry of Science and ICT (RS-2023-00281346), and an NRF grant funded by the Korean government (MEST) (RS-2023-00208341). **Author contributions:** Conceptualization: S.K.P., Y.-H.K., J.M.L., S.W.C., C.J., and D.Y.K. Methodology: S.K.P., J.M.L., S.W.C., C.J., S.H.Y., and D.Y.K. Investigation: J.M.L., C.J., J.-W.J., and D.Y.K. Visualization: S.K.P., J.M.L., J.-W.J., J.S.P., J.K., and D.Y.K. Supervision: S.K.P., J.M.L., and D.Y.K. Writing—original draft: S.K.P., Y.-H.K., J.M.L., S.W.C., and D.Y.K. Writing—review and editing: S.K.P., J.M.L., S.H.Y., J.-W.J., and D.Y.K. Formal analysis: J.M.L. and D.Y.K. Software: D.Y.K. Project administration: S.K.P., Y.-H.K., J.M.L., and D.Y.K. Validation: S.K.P., J.M.L., J.K., and D.Y.K. Data curation: S.K.P., J.M.L., and D.Y.K. Funding acquisition: S.K.P., J.M.L., and D.Y.K. Resources: S.K.P., J.M.L., J.S.P., S.H.Y., and D.Y.K. **Competing interests:** The authors declare that they have no competing interests. **Data and materials availability:** All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials.

Submitted 22 April 2024

Accepted 30 August 2024

Published 4 October 2024

10.1126/sciadv.adp9885