Supplementary Materials for

Stretchable broadband photo-sensor sheets for nonsampling, source-free, and label-free chemical monitoring by simple deformable wrapping

Kou Li, Teppei Araki, Ryogo Utaki, Yu Tokumoto, Meiling Sun, Satsuki Yasui, Naoko Kurihira, Yuko Kasai, Daichi Suzuki, Ruben Marteijn, Jaap M.J. den Toonder, Tsuyoshi Sekitani*, Yukio Kawano*

*Corresponding author. Email: sekitani@sanken.osaka-u.ac.jp (T.S.); kawano@elect.chup-u.ac.jp (Y.Kaw.)

Published 11 May 2022, Sci. Adv. 8, eabm4349 (2022)
DOI: 10.1126/sciadv.abm4349

This PDF file includes:

- Figs. S1 to S30
- Table S1
- References
Fig. S1. The photo-thermoelectric (PTE) effect on a PN-type single-walled carbon nanotube (SWCNT) film.

In the equation shown in (A), $\Delta V$, $S_{P\text{ type CNT film}}$, $S_{N\text{ type CNT film}}$, and $\Delta T$ respectively correspond to the PTE voltage response, Seebeck coefficients of P- and N-type CNT films, and photo-induced thermal gradient in the channel. Chemical carrier doping in the Materials and Methods section describes details of the PN-interface formation on CNT films. In this study, the PTE effect was employed for its advantageous functionality among several types of photo-detection methods, such as the broadband photo-detection compared to electron-type detectors and uncooled photo-detection compared to photon-type detectors (61).

While several candidate materials for thin-film type photo-detectors such as graphene (62), CNT (63), MoS2 (64), SnSe (65), NbS3 (66), and PEDOT:PSS (67), CNT films are employed as the photo-absorbent channel in this study for their functional physical characteristics. CNT films collectively exhibit mechanical strength (68), flexibility (69), and advantageous excellent uncooled broadband photo-absorption (70). Together with the Seebeck coefficients of CNT films
ranging from tens to hundreds \(\mu V/K\) (71–73) which are comparable to or exceed the typical Seebeck coefficient values of PEDOT:PSS and so on, the use of CNT films allows efficient broadband operations and conversion of photo-irradiation power to electrical signals with good PTE properties while flexibly adjusting target structures.

Regarding the proposed CNT film channel structure, the PN-junction was formed to facilitate the higher photo-response detection. The PTE response is proportional to the effective Seebeck coefficient: \(S_{\text{Eff}}\) of the photo-detection interface. \(S_{\text{Eff}}\) can be obtained by the difference in Seebeck coefficients of each different material employed for the photo-detection interface. The PN-junction formation facilitates an enhancement of \(S_{\text{Eff}}\): \(S_{\text{P type CNT film}}\) (ranging around 40 \(\mu V/K\)) – \(S_{\text{N type CNT film}}\) (ranging around –50 \(\mu V/K\)) (B–D). Here, PTE responses of respective photo-detection interfaces can be described as follows:

\[
\Delta V = S_{\text{Eff}} \times \Delta T = (S_{\text{N type CNT film}} - S_{\text{Electrode}}) \times \Delta T
\]  
(1)

\[
\Delta V = S_{\text{Eff}} \times \Delta T = (S_{\text{P type CNT film}} - S_{\text{N type CNT film}}) \times \Delta T
\]  
(2)

\[
\Delta V = S_{\text{Eff}} \times \Delta T = (S_{\text{Electrode}} - S_{\text{P type CNT film}}) \times \Delta T
\]  
(3)

While the \(S_{\text{Eff}}\) of the PN-junction is maximized and larger than the fundamental Seebeck coefficient of the CNT film itself: \(S_{\text{P type CNT film}}\), \(S_{\text{Eff}}\) of the device structure without the PN-junction of a channel-electrode (ranging around 1.5 \(\mu V/K\)) interface is suppressed.

(B) The dopant dripping is performed by methods such as casting or inkjet application. After the half-side coating of the CNT film channel with the N-type chemical carrier dopant, a presented boundary serves as the PN junction and photo-detection interface. (C) Change in the Seebeck coefficient of the CNT film channel before and after the doping. The doping was performed at 300 s of the horizontal axis of the graph. The entire surface of the channel evaluated here was coated with the dopant. The Seebeck coefficient of the channel was continuously recorded to a digital multimeter (27), and the measurement speed was 4 scan/s. (D) Continuous mapping of PTE responses of the proposed PTE sensor sheet along the channel length direction. A laser fiber for photo-irradiation was scanned from a channel-electrode junction (①: Eq. S1) to the remaining channel-electrode junction (③: Eq. S3), including the PN-junction (②: Eq. S2) in the middle.
Fig. S2. Transparency of a thin polyurethane (PU) film in terahertz (THz) and infrared (IR) frequency regions.

High broad transparency ranging from 83 % to 100 % (λ (THz): 66.7–600 μm, λ (IR): 2.5–5 μm) was observed for an 8-μm-thick PU thin-film. The PU film (Silklon) was employed for the channel sealing layer (fig. S3) and can be regarded as one of the preferable sealing layer materials for broadband photo-detectors, together with the transparency in the visible light frequency region as shown in the photograph. THz-TDS, and FTIR of the Materials and Methods section describes the corresponding details.
Fig. S3. Fabrication of the stretchable photo-thermoelectric sensor sheet. (A) Schematic fabrication flow of the proposed device. (B) Photographs of the device with a multi-pixel array, consisting of carbon nanotube (CNT) film channels, polyurethane (PU) supporting and sealing substrates, elastic electrodes, and a partial epoxy stiffener.
Fig. S4. Thermal durability and optical stability evaluation of carbon nanotube (CNT) film photo-thermoelectric (PTE) sensors.

(A) Experimental setup. Thermal durability and optical stability evaluation of CNT film PTE sensors of the Materials and Methods section describes the corresponding details. (B) Continuous mapping of PTE responses of the proposed device along the channel length direction with different channel annealing temperatures under near-infrared (NIR: $\lambda = 870$ nm) scanning. The device was annealed 3 minutes for each temperature, and the typical single-peak PTE response mapping (32) was maintained up to 200 °C. This infers the wet-processed chemical carrier doping on CNT films is functional even under high-temperature operation. (C) Change in PTE responses of the device with different channel annealing temperatures under the NIR irradiation. The stability of the PTE conversion in response to the channel annealing temperature was observed. Each plotted PTE response equals differences of photo-responses with (at 10 mm of the horizontal axis in (B): peak response at the PN junction) and without (0–5 mm of the horizontal axis in (B): open-circuit voltage response) photo-irradiation to the device. Photodetection with the device additionally results in local temperature increments to the reference device temperature owing to photo-absorption at the photo-detection interface. In other words, the photo-detection interface of the PN junction exhibits the highest temperature throughout the channel during photo-detection with the device in accordance with the operating mechanism of the PTE effect. Thus, the photo-induced temperature gradient across the channel and associated device PTE response functions uniformly for changes in the reference device temperature based on the above demonstrations. (D) Change in PTE responses of the device with NIR irradiation under the continuous channel annealing at the temperature of 150 °C up to 60 minutes. The result indicates the wet-processed chemical carrier doping on CNT films is also functional under the...
continuous high-temperature operation. Note that the annealing condition of the actual device fabrication is up to 100 °C for 60 minutes, this guarantees PN-type CNT film channels can be well embeddable in the stretchable framework without intense PTE performance degradation. The plots in (C) and (D) were obtained via dividing PTE responses of the device at each annealing temperature or annealing time by the initial device photo-response value before annealing.
Fig. S5. **Thickness profiles of partially stiffened polyurethane substrates.**
Thickness distributions were obtained by utilizing a stylus profilometer.
Fig. S6. Specific geometric model for the strain distribution analysis.
(A) Top view of the partially stiffened polyurethane substrate. A quarter circle corresponds to the epoxy stiffener. (B) Stiffener topologies.
Fig. S7. Elasticity characterization of the stretchable polyurethane (PU) substrate and electrode under large strains.

(A) Experimental setup for measuring the stress and the electrical resistance of a complex-layered specimen that is substrate/electrode. The measurements were performed under the condition of repetitive cycles for 20 %, 50 %, and 100 % strain. Change in electrical resistance ($\Delta R/R_o$) under the cyclic strains was measured using electrode on (B) single type and (C) composite type of PU substrate (Silklon; Excellent; and MG, Takeda Sangyo Co.). Initial resistance of $R_o$ was 0.2–0.9 $\Omega$ for all electrodes. In this study, electrode fabrication was basically conducted using a Silklon-PU substrate. The resistance of electrodes on the Silklon-PU substrate was over 100 times higher at 100% strain than $R_o$ in (B). The increment of the resistance was suppressed using a composite substrate of Silklon/Ecellent/Silklon and laminate of Silklon (C and figs. S8A, C).
Fig. S8. Dependence of the annealing condition and polyurethane (PU) substrate types for the electrical resistance change.

(A) Change in electrical resistance ($\Delta R/R_0$) of electrodes on different types of PU substrates under uniaxial strain. Comparison of the electrical resistance change with (B) different annealing conditions on MG-PU substrates and (C) different types of PU substrates (Silklon; Ecellent; and MG). Measurements were performed under 100 cycles of 0–20 % strain. These investigations suggest the types of substrate property significantly differ in the electrical resistance change ratio of electrodes, and the MG-PU substrate is the best candidate among single type PU substrates. The MG-PU substrate showed the thickest thickness and largest Young’s modulus with the minimum fatigue among the present candidates (figs. S9A–B). These physical properties bring the improvement on the contraction to 0 % strain of electrodes. Consequently, the utilization of the MG-PU substrate leads to the smallest electrical resistance increment of electrodes against cyclic strains (C and fig. S7B). In this work, the Ecellent and Silklon-PU substrates were employed to fabricate the stretchable photo-thermoelectric (PTE) sensor sheet using sealing process. Although Silklon-PU substrate exhibits maximum fatigue (fig. S9B), the increment of the resistance was suppressed using a composite substrate of Silklon/Ecellent/Silklon and sealing of Silklon (A, C and fig. S7C). In addition, the proposed stretchable PTE sensor sheet performs the stable photo-response against mechanical deformations owing to an embedded stiffener.
Fig. S9. Tensile property evaluation for different types of polyurethane (PU) substrates. 
(A) Comparison of the stress-stroke and stress-strain characteristics with PU-substrates of 
Silklon, Excellent, and MG (Thickness: 8 µm, 70 µm, and 100 µm, respectively; Width: 4 mm 
for all; Modulus at 100 % strain: 6.7, 3.5, and 10.9 MPa, respectively). Each data was averaged 
among three samples for each type. (B) Comparison of the repetitive load-stroke characteristics 
with the PU-substrates against 100-cycles for 20 % strain, 60 %-strain, and 100 %-strain. 
Tension decrease and residual strain were inserted in (B), implying the degree of fatigue. The
order of the tension decrease (Silklon, Ecellent, and MG) corresponds instability of electrical resistance under cyclic strains (figs. S7B and S8C).
Fig. S10. Fundamental characteristics of the photo-thermoelectric (PTE) sensor sheet against mechanical stretching.

(A) Photographs of the devices consisting of transferred channels with and without the stiffener structure while being stretched. The device in the top hand side of photographs has a partial epoxy stiffener on the rear side of the carbon nanotube (CNT) film channel. On the other hand, there is no stiffener for one in the bottom hand side of photographs. The photographs indicates the stiffener relaxes strain on the channel region and enables higher stretchable device operations. As shown in the photograph of the 100 % strain, the device breakage point can be observed at a boundary of the partial stiffener. (B) Photographs of the devices consisting of printed channels with and without the stiffener structure while being stretched. (C) Noise voltage mappings of the proposed device for different strains. As the channel region dominantly governs the device resistance (sub-1 Ω for electrodes among the total resistance of over 1 kΩ), the stiffener helps avoid significant changes in channel-stretching-induced resistance and the associated noise voltage. Here, noise voltages of the CNT film PTE sensors can be approximated to the lower limit of the thermal noise value since the devices function without applying bias voltages (27). NEP evaluation of the Materials and Methods section describes the corresponding details. The peak value at 50 Hz originates from the power source of the measurement system (not from the device itself).
Fig. S11. Angle dependence for the device stretchability.
(A) Mapping of photo-response signals of the proposed device under external near-infrared irradiation (NIR: $\lambda = 870$ nm) against omni-directional stretching. As shown in the scheme, the effective tension strain: $F_{\text{Eff}}$ on the device along the channel and electrode length direction can be estimated to be the cosine component of the applied tension strain: $F$. (B) Mapping of the strains at the device breakage points and the associated $F_{\text{Eff}}$ (tension strain along the device length direction) for evaluated device stretching angles of 0°, 30°, 60°, and 90°. The graph infers device stretching at the angles where $F_{\text{Eff}}$ behaves smaller result in higher device stretchability.
Fig. S12. Durability and optical stability of the stretchable photo-thermoelectric (PTE) sensor sheet against mechanical vacuum crumpling.

6,700 Pa was applied to the device, and a near-infrared light emitting diode (NIR LED: $\lambda = 870$ nm) was employed as the external photo source. The presenting result infers the device durability allows stable photo-detection operations even under repetitive crumpling on the proposed stretchable PTE sensor sheet.
Fig. S13. Measurement setup for the photo-induced direct current (DC) voltage response signal mapping against mechanical device deformations.

(A) Schematic of the digital controlled device stretching measurement, and a flowchart of the corresponding LabVIEW program. To avoid the misalignment of the focal point for the near-infrared (NIR) irradiation, the center region of the carbon nanotube film channel was fixed from the backside with an optical jig. (B) Simple experimental diagram for monitoring photo-response signals of the proposed device against repetitive stretching. (C) Simple experimental diagram for monitoring photo-response signals of the proposed device against omni-directional stretching. (D) Schematic of the device vacuum crumples. PTE response against mechanical deformations of the Materials and Methods section describes the corresponding details.
Fig. S14. Fabrication of the stretchable photo-thermoelectric sensor sheet with series integration of multiple PN-type carbon nanotube (CNT) film pixels.
Fig. S15. Photo-thermoelectric conversion with the multi-PN-pixel series integration.
(A) Schematic of the photo-detection with the proposed structure. (B) Photograph of the channel. (C) Seebeck effect on the proposed structure.

\[
\Delta V_1 = \Delta V_2 = \Delta V_3 = \cdots = \Delta V_n = (S_{P\text{-CNT film}} - S_{N\text{-CNT film}}) \Delta T
\]

\[
\Delta V_{\text{total}} = n(S_{P\text{-CNT film}} - S_{N\text{-CNT film}}) \Delta T
\]
Fig. S16. Photo-detection sensitivity distribution in broad infrared (IR) regions of the proposed device.

In this work, the final photo-detection sensitivity in terms of noise equivalent power (NEP) values of the proposed photo-thermoelectric sensor is as follows: 3.87 pWHz\(^{-1/2}\) in \(\lambda = 10.3\ \mu m\) (\(\Delta V = 12\ \text{mV}\), \(P_{\text{Eff}} = 256\ \text{nW/ch}\), Beam spot: 20-mm\(\varphi\)-collimated), 4.5 pWHz\(^{-1/2}\) in \(\lambda = 4.33\ \mu m\) (\(\Delta V = 10.4\ \text{mV}\), \(P_{\text{Eff}} = 260\ \text{nW/ch}\), Beam spot: 5-mm\(\varphi\)-collimated), 8.68 pWHz\(^{-1/2}\) in \(\lambda = 870\ \text{nm}\) (\(\Delta V = 3.22\ \text{mV}\), \(P_{\text{Eff}} = 155\ \text{nW/ch}\), Beam spot: 5-mm\(\varphi\)-collimated), for the device with the electrical resistance of 20 k\(\Omega\). Here, \(P_{\text{Eff}}\) corresponds to the effective power of the light irradiation on the photo-detection interface.

Simultaneously, associated \(D^*\) values of the proposed device are as follows: \(2.62 \times 10^9\ \text{cmHz}^{1/2}\text{W}^{-1}\) in \(\lambda = 10.3\ \mu m\) (\(A_{\text{Eff}} = 1.03 \times 10^{-4}\ \text{cm}^2\)), \(1.46 \times 10^9\ \text{cmHz}^{1/2}\text{W}^{-1}\) in \(\lambda = 4.33\ \mu m\) (\(A_{\text{Eff}} = 4.33 \times 10^{-5}\ \text{cm}^2\)), \(3.48 \times 10^8\ \text{cmHz}^{1/2}\text{W}^{-1}\) in \(\lambda = 870\ \text{nm}\) (\(A_{\text{Eff}} = 8.70 \times 10^{-6}\ \text{cm}^2\)) for the channel size of 3-mm-length and 1-mm-width (100-\(\mu m\)-width/ch \(\times\) 10). Here, \(A_{\text{Eff}}\) corresponds to the effective area of the photo-detection interface under the light irradiation in each wavelength regions, and \(D^*\) can be described by the following equation:

\[
D^* = \frac{\sqrt{A_{\text{Eff}}}}{\text{NEP}}
\]  
(4)
Fig. S17. Experimental diagrams for the transmissive terahertz (THz, $\lambda = 577$ µm) imaging with the multi-pixel series integrated stretchable photo-thermoelectric (PTE) sensor sheet. (A) Comparison of the obtained transmissive images of a metal clip, which was concealed on an opaque silicon board. In the obtained PTE images, horizontal and vertical axes correspond to the X and Y scanning directions. (B) Comparison of the obtained transmissive images of a concealed metal washer with different device strains. The proposed device was kept being stretched for 20 % strain, 50 % strain, and 100 % strain in a manner described in fig. S13A.
Fig. S18. Transient photo-response of the stretchable multi-PN-pixel-series-integrated photo-thermoelectric (PTE) sensor sheet.
Fig. S19. Experimental diagram for the black-body radiation (BBR)-based passive multi-view wrapping photo-thermoelectric (PTE) imaging of the liquid flow position.

(A) Simple diagram for setting up the measurement shown in Fig. 5D. Here, a 10-pixel stretchable PTE sensor array sheet firmly attaches to the outer surface of the opaque polyvinyl chloride (PVC) pipe. Employment of such multi pixels facilitates sensing of the liquid-flowing-induced BBR with the multi-view monitoring angle. (B) Sectional schematics of the outer surface wrapping configurations of liquid flowing pipes with the proposed device. The more the number of the PTE sensor pixel becomes, the wider covering and available monitoring areas range. This scheme thus eases multi-view visualization of targets without employing bulky rotation stages. (C) Potential use of the multi-pixel PTE sensor array sheet, where the device firmly attaches to the outer surface of three-dimensional curvilinear targets such as a syringe.
Fig. S20. Fundamental characteristics of the simple liquid sensing.

(A) Photograph of the proposed device equipped to monitor black-body radiation (BBR) from liquid circulation, and thermal images obtained during the experiment. The optical path length, which is the distance between the soft tube and the device, is maintained at 1 mm in accordance
with the experimental conditions of Fig. 5F. The obtained thermal images depict the device temperatures during BBR detection at 15, 30, 45, and 60 minutes after the liquid starts circulating. The value shown in each thermal image corresponds to the temperature at the center of the device (marked with “x”). Commercial thermography (Infrared Thermography, testo 868, Testo K.K.) captured these thermal images. (B) Mapping of the PTE responses of the device for (A). Along with the aforementioned thermal images, stable behaviors were observed for both the temperature gradient across the device and associated BBR-induced PTE responses. (C) Changes in BBR-induced PTE responses of the device against the optical path length. The longer the optical path length, the weaker was the device response. The obtained result also indicates that the BBR from the liquid dominantly affects PTE responses of the device during the passive sensing experiments. The PTE responses of the device originating from the external experimental environment, i.e., values after 50 mm along the horizontal axis in the graph, are less than one hundredth of the value obtained with an optical path length of 1 mm.
Fig. S21. Photograph of the thermostatic liquid circulation setup.

Here, the liquid temperature and room temperature are maintained to 40 °C and 22 °C, respectively. In this scheme, soft tubes were wrapped with the stretchable photo-thermoelectric sensor sheet while the liquid monitoring measurement. There is an agitator in a bottle, and liquids confined in the bottle were stirred at a speed of 1,200 rpm after chemicals adding.
Fig. S22. Simple comparison of the rigid photo-thermoelectric (PTE) sensor configuration and the PTE sensor wrapping configuration for the passive liquid sensing applications. (A) Change in black-body radiation (BBR)-induced passive PTE responses before and after the chemicals dissolution in purified water circulating in a soft rubber tube, obtained by employing the carbon nanotube (CNT) film PTE sensor in a rigid configuration. The presented signal reduction starting from 100 s of the horizontal axis in the graph corresponds to the local absorption of BBR from the solvent with in-liquid chemicals. Here, the CNT film PTE sensor was mounted on a commercial plastic printed circuit board, and the optical path length between the device and the tube was 1 mm. (B) Change in BBR-induced passive PTE responses before and after the chemicals dissolution in the solvent obtained wrapping the soft rubber circulation tube with the proposed stretchable PTE sensor sheet. The graph infers the device wrapping configuration as well functions for the chemicals dissolution monitoring compared with the rigid device configuration. In other words, signal reduction of the BBR-based passive PTE responses can be also observed with the device wrapping configuration (starting from 100 s of the horizontal axis of the graph). The obtained result simultaneously indicates the device wrapping configuration enables detecting higher intensity passive PTE responses owing to further shortening of the optical path length between the device and the tube.
Fig. S23. Non-sampling and label-free passive on-site dynamic photo-monitoring of glucose dissolution, ranging a solution concentrations of 50–100 mg/dL.

(A) Change in BBR-induced passive photo-thermoelectric (PTE) responses of the proposed device against increments in solution concentrations by 50 mg/dL each. (B) Comparison of changes in BBR-induced passive PTE responses vs. 50, 100 mg/dL glucose dissolution.
Fig. 24. Fundamental analysis for the passive monitoring of in-liquid chemicals concentrations.

(A) Photo-absorption spectrum of in-liquid chemicals for different dissolution concentrations in broad infrared (IR) regions. The measurement was performed by employing the attenuated total reflection (ATR) function (Flourier transform IR spectroscopy (FTIR), 400–4,000 cm$^{-1}$). Here, the reference for the ATR-FTIR was the solvent: purified water to extract the photo-absorption with in-liquid chemicals themselves. The obtained spectral change infers the concentration of in-liquid chemicals governs the photo-absorption. (B) Simple comparison of the spectral-based photo-absorption and reduction of black-body radiation (BBR)-based passive responses of the proposed stretchable photo-thermoelectric sensor sheet against chemicals dissolution. The absorptance distribution obtained by the ATR-FTIR measurements (sample: target solution, reference: solvent purified water of the solution) was integrated as the spectral analysis since the carbon nanotube film PTE sensor detects broadband IR-irradiations. The obtained result validates the proposed passive solution concentration monitoring.
Fig. S25. Spectral investigations for the black-body radiation (BBR)-based non-sampling and label-free on-site dynamic dissolution monitoring of different chemicals.

(A) Theoretical spectral graph of BBR at the absolute temperature of 313 K ($I_{BBR}$) derived from Planck’s radiation law. In this study, spectral values ranging from 700 cm$^{-1}$ to 3,000 cm$^{-1}$ wavenumber bands were referred, matching the dominant intensity region of the BBR. (B) Transmittance spectrum of the low-pass filter ($t_{Low}$). (C) Transmittance spectrum of the soft rubber liquid circulation tube ($t_{Tube}$). (D) Photo-absorption spectrum of the carbon nanotube (CNT) film channel ($A_{CNT}$). (E) Effective photo-detection spectrum ($\Delta V_{Eff}$) which was calculated by the following equation:

$$\Delta V_{Eff} = (I_{BBR} \times t_{Low}) \times t_{Tube} \times t_{Seal} \times A_{CNT} = I_{Eff-BBR} \times t_{Tube} \times t_{Seal} \times A_{CNT} \quad (5)$$

Where $t_{Seal}$ and $I_{Eff-BBR}$ are the transmittance spectrum of the PU sealing layer (derived from fig. S2) and the practical BBR (Fig. 6F). By referring to the photo-absorption spectrum of glucose and tannic solutions ($A_{Glu}, A_{Tan}$, Fig. 6G), the spectral estimation of the BBR-absorption from the circulating solvent purified water for both in-liquid chemicals ($\Delta V_{Eff-Glu}, \Delta V_{Eff-Tan}$, Fig. 6H) were calculated as follows:
\[ \Delta v_{\text{Eff–Glu}} = \Delta V_{\text{Eff}} \times A_{\text{Glu}} \]  
(6)  
\[ \Delta v_{\text{Eff–Tan}} = \Delta V_{\text{Eff}} \times A_{\text{Tan}} \]  
(7)
Fig. S26. Spectral simulation of black-body radiation (BBR)-based passive in-liquid monitoring toward the future integration with stretchable broadband tunable filters.

(A) Schematics of the carbon nanotube (CNT) film-based stretchable photo-thermoelectric (PTE) sensor sheet being firmly wrapped around the soft tube. The device continuously monitors the BBR signals originating from the liquid circulating in the tube. Chemical dissolution causes the local BBR absorption from the solvent, and induces the associated reduction of the device BBR response. (B) Simulated data analysis diagram for BBR-based passive monitoring of respective glucose and tannic solution with the device. The response distribution of the CNT film-based stretchable PTE sensor against the BBR from the solvent serves as the background spectrum for the passive in-liquid chemicals monitoring. Here, the factors to be considered are the theoretically calculated BBR spectrum originating from the solvent (based on Planck’s law), the
transmittance spectrum of the low-pass filter and soft container tube and device sealing, and the reference absorption spectrum of the CNT film channel. Combining these parameters enables simulating the background device’s BBR response spectrum. While the chemical dissolution is occurring, a bias is applied to the reference absorption spectrum of the in-liquid chemicals based on the above background device’s BBR response. This final simulated spectrum represents the effective local absorption of the solvent’s BBR with the in-liquid chemicals and associated reduction magnitude of the device response ($\Delta v_{\text{Eff}}$ in the graph). (C) Changes in the actual BBR response of the CNT film-based stretchable PTE sensor which is firmly wrapped around the soft liquid circulation tube while the chemicals dissolve. The difference between the device’s BBR response for the respective glucose and tannic solutions indicates that the glucose dissolution results in a greater device response reduction that is 2.9 times greater than that of the tannic dissolution. Meanwhile, the spectrally simulated total reduction magnitude of the device’s BBR response for the respective glucose and tannic dissolution (B) is 2.4 times, being in good agreement with the actual experimental observation with the CNT film-based stretchable PTE sensor. In comparison with the presenting result where the total device response with broadband BBR detection can be obtained, the simulated reduction distributions ($\Delta v_{\text{Eff-Glu}}$, $\Delta v_{\text{Eff-Tan}}$) are integrated. (D) Conceptual diagram for the future integration of the deformable PTE sensor and stretchable broadband tunable filter. We believe that the device-filter integration contributes to the FTIR (Fourier transform IR spectroscopy)-like spectroscopic usage of the device. Regarding the above demonstration, each necessary spectrum was obtained by FTIR measurements in advance of the actual device monitoring, including the reference absorption of the CNT film channel and target in-liquid chemicals. In contrast, the filter integration would enable simple and direct spectrum acquisition of the background device’s BBR response and effective local absorption of the solvent’s BBR with the in-liquid chemicals by the device itself.
Fig. S27. Conceptual scheme of the proposed black-body radiation (BBR)-based in-liquid chemicals monitoring.
Fig. S28. Photograph of the proposed stretchable broadband photo-thermoelectric (PTE) sensor sheet, being wrapped on a stem and equipped with a wireless module.
Fig. S29. Wireless signal readout operation of the carbon nanotube (CNT) film photothermoelectric (PTE) sensor.

A wireless signal readout circuit (up to 8 terminals) was connected to the multipixel CNT film PTE sensor via a typical flexible printed circuit cable. Each negative end of the sensor array was grounded, and the wireless circuit recorded potential differences of each channel to the channel No. 1 (reference). (A) Device driving under far-infrared (FIR: $\lambda = 10.3 \ \mu$m) irradiation. Each pixel was irradiated one by one via the light spot scanning and the corresponding time shift of photo-responses was observed. Here, both wireless PTE signal readout on the device with (B) maximum output power irradiation and (C) minimum output power irradiation of the external FIR photo source were successfully demonstrated. (D) Wireless readout of the multi-pixel black-body radiation (BBR)-induced passive PTE responses. The author’s index finger was set at 10 mm above the device, and BBR from the finger was detected and transferred via the wireless circuit. (E) Simple demonstration of the wireless remote and real-time finger motion sensing.
Table S1. Comparison of fundamental performances among recent works on uncooled photo-detectors.

| Type (Ref.) | Mechanism | Freq.       | Speed | Min. NEP     | Structure          | Application                      |
|-------------|------------|-------------|-------|--------------|--------------------|-----------------------------------|
| This work   | PTE effect | Broad Sub-THz –NIR | 70 ms | 3.87 pWhz$^{-1/2}$ | Flexible & Stretchable 70–280 % | Liquid inspection Deformity testing Photo imaging |
| PN-CNT (32) | PTE effect | Broad Sub-THz –NIR | 13 ms | 30 pWhz$^{-1/2}$ | Flexible           | Photo imaging Photo sensing Wearable device |
| Bolometer (74) | Thermal | Broad THz–NIR | 1 ms  | 200 pWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| MEMS bolometer (18) | Thermal | Broad THz–NIR | 55 µs | 20 pWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| Golay cell (cmll.) | Thermal | Broad Sub-THz –MIR | 25 ms | 10 nWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| Pyro-electric (75) | Thermal | Sub-THz | 2.3 ms | 20 nWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| SBD (76) | Electronic | THz | 1 µs | 36.2 pWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| CMOS (77) | Electronic | Sub-THz | N.A. | 23 pWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| HEMT (78) | Electronic | Sub-THz | 38 ps | 500 fWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| Plasmonics (79) | Electronic | Sub-THz | N.A. | 480 fWhz$^{-1/2}$ | Rigid              | Photo imaging Photo sensing |
| Si IR transistor (80) | Thermal | IR | 9.7 ms | 13 pWhz$^{-1/2}$ | Rigid              | Photo sensing |
| Graphene (81) | Electronic | THz | N.A. | 3 nWhz$^{-1/2}$ | Flexible           | Photo sensing |
| Material                  | Source/Technology | Detection Mode | Response Time | Stretchability | Application                      |
|--------------------------|-------------------|----------------|---------------|----------------|----------------------------------|
| Pyrolytic Carbon         | EMW absorption    | THz            | N.A.          | Flexible & Stretchable 30 % | Photo sensing                   |
| PEDOT: PSS-ZnO           | Photovoltaic      | UV             | 30 s          | Flexible & Stretchable 30 % | Photo sensing, Deformity testing, Wearable device |
| CH$_3$NH$_3$PbI$_3$      | Photovoltaic      | Broad NIR–UV   | 68 ms         | Flexible & Stretchable 100 % | Photo sensing, Strain monitoring |
| Crumpled graphene        | Photovoltaic      | Visible light  | 269 ms        | Flexible & Stretchable 250–350 % | Photo sensing, Strain monitoring, Wearable device |
| PbS QD-P3HT              | Photovoltaic      | Broad NIR–UV   | 160 ms        | Flexible & Stretchable 100 % | Photo sensing, Strain monitoring |
| Rippled graphene         | Photovoltaic      | UV             | 10 s          | Flexible & Stretchable 25 % | Photo sensing, Strain monitoring |
| Graphene-AuNP            | Plasmonics        | Visible light  | 1 s           | Flexible & Stretchable 200 % | Photo sensing, Deformity testing, Wearable device |

*NEP: Noise equivalent power, THz: Terahertz, IR: Infrared, FIR: Far-IR, MIR: Mid-IR, NIR: Near-IR, UV: Ultraviolet, CNT: Carbon nanotube, MEMS: Micro electro mechanical systems, SBD: Schottky barrier diode, CMOS: Complementary metal-oxide semiconductor, HEMT: High electron mobility transistor, QD: quantum dot, NP: nanoparticle
Permeable THz irradiation enables non-destructive remote monitoring of chemical gas reactions which synthesize liquids. This is because of typical THz absorption by liquids. (A) Schematics of the experimental setup. Both hydrogen and oxygen gas are confined inside a plastic container. THz irradiation which passes through the container is continuously detected by the carbon nanotube (CNT) photo-thermoelectric (PTE) sensor. (B) PTE responses of the proposed device with a single channel for continuous external THz irradiation. Along with the broad and high-efficiency THz absorption characteristic of the employed semiconducting and metallic mixed type single-walled CNT films (55), the device exhibits stable THz-irradiation-induced PTE conversion. (C) Changes in the THz-irradiation-induced PTE responses of the device for gradually lowered emitter output power. The change ratios of the emitter output powers to obtained PTE responses are in good agreement, and indicate that the device is suitable for fundamental THz sensing and imaging applications. (D) Change in PTE responses obtained by the proposed device before and after piezoelectric ignition in the container. In the graph, the sudden increment of PTE responses corresponds to BBR signals from the container induced by the reaction heat. On the other hand, the attenuation of transmission PTE signals which appears after the reaction heat-induced BBR detection is caused by photo-absorption by synthesized
water. Here, 30 mL of hydrogen gas and 15 mL of oxygen gas were respectively confined in the container. (E) Changes in PTE response reduction vs. hydrogen gas content in the container. The ratio of hydrogen gas to oxygen gas inclusion is maintained at 2:1. As the gas content increases, the attenuation of the PTE responses becomes stronger. In this way, the presenting approach remotely monitors the amount of water synthesis in the gas reaction in a non-destructive manner.
REFERENCES AND NOTES

1. T. K. Liu, H. Y. Sheu, C. N. Tseng, Environmental impact assessment of seawater desalination plant under the framework of integrated coastal management. *Desalination* **326**, 10–18 (2013).

2. S. Rehfeldt, J. Stichlmair, Measurement and prediction of multicomponent diffusion coefficients in four ternary liquid systems. *Fluid Phase Equilib.* **290**, 1–14 (2010).

3. C. E. Restrepo, J. S. Simonoff, R. Zimmerman, Causes, cost consequences, and risk implications of accidents in US hazardous liquid pipeline infrastructure. *Int. J. Crit. Infrastr. Prot.* **2**, 38–50 (2009).

4. M. C. Bruzzoniti, R. M. D. Carlo, C. Sarzanini, R. Maina, V. Tumiatti, Determination of copper in liquid and solid insulation for large electrical equipment by ICP-OES. Application to copper contamination assessment in power transformers. *Talanta* **99**, 703–711 (2012).

5. K. Raunkjær, T. W. Jacobsen, P. H. Nielsen, Measurement of pools of protein, carbohydrate and lipid in domestic wastewater. *Water Res.* **28**, 251–262 (1994).

6. A. Stachniuk, E. Formal, Liquid chromatography-mass spectrometry in the analysis of pesticide residues in food. *Food Anal. Methods* **9**, 1654–1665 (2016).

7. A. C. O. Costa, L. d. S. Perfeito, M. F. M. Tavares, G. A. Micke, Determination of sorbate and benzoate in beverage samples by capillary electrophoresis—Optimization of the method with inspection of ionic mobilities. *J. Chromatogr. A* **1204**, 123–127 (2008).

8. K. A. Barnes, M. L. Anderson, J. R. Stofan, K. J. Dalrymple, A. J. Reimel, T. J. Roberts, R. K. Randell, C. T. Ungaro, L. B. Baker, Normative data for sweating rate, sweat sodium concentration, and sweat sodium loss in athletes: An update and analysis by sport. *J. Sports Sci.* **37**, 2356–2366 (2019).

9. G. Cozzi, L. Ravarotto, F. Gottardo, A. L. Stefani, B. Contiero, L. Moro, M. Brscic, P. Dalvit, Short communication: Reference values for blood parameters in Holstein dairy cows: Effects of parity, stage of lactation, and season of production. *J. Dairy Sci.* **94**, 3895–3901 (2011).
10. H. R. El-Ramady, T. A. Alshaal, S. A. Shehata, É. D.-Szabolcsy, N. Elhawat, J. Prokisch, M. Fári, L. Marton, Plant nutrition: From liquid medium to micro-farm. *Sustain. Agr. Rev.* **14**, 449–508 (2014).

11. W. Al-Faqheri, T. H. G. Thio, M. A. Qasaimeh, A. Dietzel, M. Madou, A. Al-Halhouli, Particle/cell separation on microfluidic platforms based on centrifugation effect: A review. *Microfluid. Nanofluidics* **21**, 102 (2017).

12. C. V. Nguyen, A. V. Nguyen, A. Doi, E. Dinh, T. V. Nguyen, M. Ejtemaei, D. Osborne, Advanced solid-liquid separation for dewatering fine coal tailings by combining chemical reagents and solid bowl centrifugation. *Sep. Purif. Technol.* **259**, 118172 (2021).

13. X. M. Piao, E. J. Cha, S. J. Yun, W. J. Kim, Role of exosomal miRNA in bladder cancer: A promising liquid biopsy biomarker. *Int. J. Mol. Sci.* **22**, 1713 (2021).

14. T. Kaya, G. Liu, J. Ho, K. Yelamarthi, K. Miller, J. Edwards, A. Stannard, Wearable sweat sensors: Background and current trends. *Electroanalysis* **31**, 411–421 (2019).

15. P. Gallo, S. Fabbrocino, G. Dowling, M. Salini, M. Fiori, G. Perretta, L. Serpe, Confirmatory analysis of non-steroidal anti-inflammatory drugs in bovine milk by high-performance liquid chromatography with fluorescence detection. *J. Chromatogr. A* **1217**, 2832–2839 (2010).

16. X. Wen, Q. Yang, Z. Yan, Q. Deng, Determination of cadmium and copper in water and food samples by dispersive liquid–liquid microextraction combined with UV–vis spectrophotometry. *Microchem. J.* **97**, 249–254 (2011).

17. A. Rogalski, Semiconductor detectors and focal plane arrays for far-infrared imaging. *Opto-Electron. Rev.* **21**, 406–426 (2013).

18. Y. Zhang, Y. Watanabe, S. Hosono, N. Nagai, K. Hirakawa, Room temperature, very sensitive thermometer using a doubly clamped microelectromechanical beam resonator for bolometer applications. *Appl. Phys. Lett.* **108**, 163503 (2016).
19. M. Long, Y. Wang, P. Wang, X. Zhou, H. Xia, C. Luo, S. Huang, G. Zhang, H. Yan, Z. Fan, X. Wu, X. Chen, W. Lu, W. Hu, Palladium diselenide long-wavelength infrared photodetector with high sensitivity and stability. ACS Nano 13, 2511–2519 (2019).

20. K. Li, R. Yuasa, R. Utaki, M. Sun, Y. Tokumoto, D. Suzuki, Y. Kawano, Robot-assisted, source-camera-coupled multi-view broadband imagers for ubiquitous sensing platform. Nat. Commun. 12, 3009 (2021).

21. D. Suzuki, K. Li, K. Ishibashi, Y. Kawano, A terahertz video camera patch sheet with an adjustable design based on self-aligned, 2D, suspended sensor array patterning. Adv. Funct. Mater. 31, 2008931 (2021).

22. D. Suzuki, Y. Kawano, Flexible terahertz imaging systems with single-walled carbon nanotube films. Carbon 162, 13–24 (2020).

23. Y. Nonoguchi, M. Nakano, T. Murayama, H. Hagino, S. Hama, K. Miyazaki, R. Matsubara, M. Nakamura, T. Kawai, Simple salt-coordinated n-type nanocarbon materials stable in air. Adv. Funct. Mater. 26, 3021–3028 (2016).

24. T. Araki, Y. Okabe, N. Kurihira, Y. Kasai, Y. Noda, T. Sekitani, Low-temperature printable and stretchable circuit board and its application to flexible hybrid electronics, in 2021 International Conference on Electronics Packaging (IEEE, 2021), pp. 61–62.

25. T. Yamada, Y. Hayamizu, Y. Yamamoto, Y. Yomogida, A. Izadi-Najafabadi, D. N. Futaba, K. Hata, A stretchable carbon nanotube strain sensor for human-motion detection. Nat. Nanotechnol. 6, 296–301 (2011).

26. S. Ryu, P. Lee, J. B. Chou, R. Xu, R. Zhao, A. J. Hart, S. G. Kim, Extremely elastic wearable carbon nanotube fiber strain sensor for monitoring of human motion. ACS Nano 9, 5929–5936 (2015).

27. K. Li, D. Suzuki, Y. Kawano, Series photothermoelectric coupling between two composite materials for a freely attachable broadband imaging sheet. Adv. Photon. Res. 2, 2000095 (2021).
28. J. Sun, Y. Zhu, W. Feng, Q. Ding, H. Qin, Y. Sun, Z. Zhang, X. Li, J. Zhang, X. Li, Y. Shangguan, L. Jin, Passive terahertz imaging detectors based on antenna-coupled high-electron-mobility transistors. *Opt. Express* **28**, 4911–4920 (2020).

29. J. Zhou, M. A. R. Miah, Y. Yu, A. C. Zhang, Z. Zeng, S. Damle, I. A. Niaz, Y. Zhang, Y. H. Lo, Room-temperature long-wave infrared detector with thin double layers of amorphous germanium and amorphous silicon. *Opt. Express* **27**, 37056–37064 (2019).

30. J. B. Wang, W. Li, B. Chu, C. S. Lee, Z. Su, G. Zhang, S. H. Wu, F. Yan, High speed responsive near infrared photodetector focusing on 808nm radiation using hexadecafluoro-copper-phthalocyanine as the acceptor. *Org. Electron.* **12**, 34–38 (2011).

31. R. Bogue, Terahertz imaging: A report on progress. *Sens. Rev.* **29**, 6–12 (2009).

32. D. Suzuki, Y. Ochiai, Y. Nakagawa, Y. Kuwahara, T. Saito, Y. Kawano, Fermi-level-controlled semiconducting-separated carbon nanotube films for flexible terahertz imagers. *ACS Appl. Nano Mater.* **1**, 2469–2475 (2018).

33. X. Gou, H. Xiao, S. Yang, Modeling, experimental study and optimization on low-temperature waste heat thermoelectric generator system. *Appl. Energy* **87**, 3131–3136 (2010).

34. P. Kang, M. C. Wang, P. M. Knapp, S. Nam, Crumpled graphene photodetector with enhanced, strain-tunable, and wavelength-selective photoresponsivity. *Adv. Mater.*, **28**, 4639–4645 (2016).

35. C. W. Chinag, G. Haider, W. C. Tan, Y. R. Liou, Y. C. Lai, R. Ravindranath, H. T. Chang, Y. F. Chen, Highly stretchable and sensitive photodetectors based on hybrid graphene and graphene quantum dots. *ACS Appl. Mater. Interfaces* **8**, 466–471 (2016).

36. X. Xu, Y. Zuo, S. Cai, X. Tao, Z. Zhang, X. Zhou, S. He, X. Fang, H. Peng, Three-dimensional helical inorganic thermoelectric generators and photodetectors for stretchable and wearable electronic devices. *J. Mater. Chem. C* **6**, 4866–4872 (2018).
37. P. K. Crane, R. Walker, R. A. Hubbard, G. Li, D. M. Nathan, H. Zheng, S. Haneuse, S. Craft, T. J. Montine, S. E. Kahn, W. McCormick, S. M. McCurry, J. D. Bowen, E. B. Larson, Glucose levels and risk of dementia. *N. Engl. J. Med.* **369**, 540–548 (2013).

38. Z. Li, Y. Zhu, W. Zhang, C. Xu, Y. Pan, Y. Zhao, A low-cost and high sensitive paper-based microfluidic device for rapid detection of glucose in fruit. *Food Anal. Methods* **10**, 666–674 (2017).

39. H. Suto, F. Kataoka, N. Kikuchi, R. O. Knuteson, A. Butz, M. Haun, H. Buijs, K. Shiomi, H. Imai, A. Kuze, Thermal and near-infrared sensor for carbon observation fourier transform spectrometer-2 (TANSO-FTS-2) on the greenhouse gases observing SATellite-2 (GOSAT-2) during its first year in orbit. *Atmos. Meas. Tech.* **14**, 2013–2039 (2021).

40. T. Hamazaki, Y. Kaneko, A. Kuze, K. Kondo, Fourier transform spectrometer for greenhouse gases observing satellite (GOSAT), in *Proc. SPIE 5659 Enabling Sensor and Platform Technologies for Spaceborne Remote Sensing* (SPIE, 2005), pp. 73–80.

41. C. P. Walsh, Remote sensing of atmospheric trace gases by ground-based solar fourier transform infrared spectroscopy, in *Fourier Transforms: New Analytical Approaches and FTIR Strategies*, G. Nikolić, Ed. (InTech, 2011), pp. 459–478.

42. M. Zhou, P. Wang, B. Langerock, C. Vigouroux, C. Hermans, N. Kumps, T. Wang, Y. Yang, D. Ji, L. Ran, J. Zhang, Y. Xuan, H. Chen, F. Posny, V. Duflot, J. M. Metzger, M. D. Mazière, Ground-based Fourier transform infrared (FTIR) O$_3$ retrievals from the 3040 cm$^{-1}$ spectral range at Xianghe, China. *Atmos. Meas. Tech.* **13**, 5379–5394 (2020).

43. R. Olbrycht, M. Kałuża, Optical gas imaging with uncooled thermal imaging camera—Impact of warm filters and elevated background temperature. *IEEE Trans. Ind. Electron.* **67**, 9824–9832 (2020).

44. J. E. Kim, S. S. Kim, C. Zuo, M. Gao, D. Vak, D. Y. Kim, Humidity-tolerant roll-to-roll fabrication of perovskite solar cells via polymer-additive-assisted hot slot die deposition. *Adv. Funct. Mater.* **29**, 1809194 (2019).
45. Z. Gao, C. Bumgardner, N. Song, Y. Zhang, J. Li, X. Li, Cotton-textile-enabled flexible self-sustaining power packs via roll-to-roll fabrication. Nat. Commun. 7, 11586 (2016).

46. K. Chen, W. Gao, S. Emaminejad, D. Kiriya, H. Ota, H. Y. Y. Nyein, K. Takei, A. Javey, Printed carbon nanotube electronics and sensor systems. Adv. Mater. 28, 4397–4414 (2016).

47. S. Nakata, T. Arie, S. Akita, K. Takei, Wearable, flexible, and multifunctional healthcare device with an ISFET chemical sensor for simultaneous sweat pH and skin temperature monitoring. ACS Sens. 2, 443–448 (2017).

48. V. P. Rachim, W. Chung, Multimodal wrist biosensor for wearable cuff-less blood pressure monitoring system. Sci. Rep. 9, 7947 (2019).

49. F. Larachi, D. Aksenova, B. Yousefi, X. P. V. Maldague, G. Beaudoin, Thermochemical monitoring of brucite carbonation using passive infrared thermography. Chem. Eng. Process. 130, 43–52 (2018).

50. B. R. Cosofret, W. J. Marinelli, T. E. Ustun, C. M. Gittins, M. T. Boies, M. F. Hinds, D. C. Rossi, R. L. Coxe, S. D. Chang, B. D. Green, T. Nakamura, Passive infrared imaging sensor for standoff detection of methane leaks, in Proc. SPIE 5584 Chemical and Biological Standoff Detection II (SPIE, 2004); doi.org/10.1117/12.581190.

51. M. Kowalski, Hidden object detection and recognition in passive terahertz and mid-wavelength infrared. J. Infrared Millim. Terahertz Waves 40, 1074–1091 (2019).

52. Y. Cheng, Y. Wang, Y. Niu, Z. Zhao, Concealed object enhancement using multi-polarization information for passive millimeter and terahertz wave security screening. Opt. Express 28, 6350–6366 (2020).

53. D. Suzuki, S. Oda, Y. Kawano, A flexible and wearable terahertz scanner. Nat. Photon. 10, 809–813 (2016).

54. V. Hers, D. Corbugy, I. Joslet, P. Hermant, J. Demarteau. B. Delhugne, G. Vandermoten, J. P. Hermanne, New concept using passive infrared (PIR) technology for a contactless detection of
breathing movement: A pilot study involving a cohort of 169 adult patients. *J. Clin. Monit. Comput.* **27**, 521–529 (2013).

55. D. Suzuki, Y. Ochiai, Y. Kawano, Thermal device design for a carbon nanotube terahertz camera. *ACS Omega* **3**, 3540–3547 (2018).

56. V. Giurgiutiu, K. Reifsnider, R. Kriz, B. Ahn, J. Lesko, Influence of fiber coating and interphase on the design of polymeric composite strength—Analytical predictions, in *36th Structures, Structural Dynamics and Materials Conference* (AIAA, 1995); doi.org/10.2514/6.1995-1212.

57. M. Miwa, A. Takeimo, H. Yamazaki, A. Watanabe, Strain rate and temperature dependence of shear properties of epoxy resin. *J. Mater. Sci.* **30**, 1760–1765 (1995).

58. D. J. O’Brien, N. R. Sottos, S. R. White, Cure-dependent viscoelastic Poisson’s ratio of epoxy. *Exp. Mech.* **47**, 237–249 (2007).

59. H. J. Qi, M. C. Boyce, Stress–strain behavior of thermoplastic polyurethanes. *Mech. Mater.* **37**, 817–839 (2005).

60. V. Kanyanta, A. Ivankovic, Mechanical characterisation of polyurethane elastomer for biomedical applications. *J. Mech. Behav. Biomed.* **3**, 51–62 (2010).

61. T. Otsuji, Trends in the research of modern terahertz detectors: Plasmon detectors. *IEEE Trans. Terahertz Sci. Technol.* **5**, 1110–1120 (2015).

62. D. Zhang, Y. Song, L. Ping, S. Xu, D. Yang, Y. Wang, Y. Yang, Photo-thermoelectric effect induced electricity in stretchable graphene-polymer nanocomposites for ultrasensitive strain sensing. *Nano Res.* **12**, 2982–2987 (2019).

63. X. He, N. Fujimura, J. M. Lloyd, K. J. Erickson, A. A. Talin, Q. Zhang, W. Gao, Q. Jiang, Y. Kawano, R. H. Hauge, F. Léonard, J. Kono, Carbon nanotube terahertz detector. *Nano Lett.* **14**, 3953–3958 (2014).
64. M. He, Y. J. Lin, C. M. Chiu, W. Yang, B. Zhang, D. Yun, Y. Xie, Z. H. Lin, A flexible photothermoelectric nanogenerator based on MoS$_2$/PU photothermal layer for infrared light harvesting. *Nano Energy* **49**, 588–595 (2018).

65. Y. Zhong, L. Zhang, V. Linseis, B. Qin, W. Chen, L. D. Zhao, H. Zhu, High-quality textured SnSe thin films for self-powered, rapid-response photothermoelectric application. *Nano Energy* **72**, 104742 (2020).

66. W. Wu, Y. Wang, Y. Niu, P. Wang, M. Chen, J. Sun, N. Wang, D. Wu, Z. Zhao, Thermal localization enhanced fast photothermoelectric response in a quasi-one-dimensional flexible NbS$_3$ photodetector. *ACS Appl. Mater. Interfaces* **12**, 14165–14173 (2020).

67. M. Zhang, J. T. W. Yeow, A flexible, scalable, and self-powered mid-infrared detector based on transparent PEDOT:PSS/graphene composite. *Carbon* **156**, 339–345 (2020).

68. A. Cao, P. L. Dickrell, W. G. Sawyer, M. N. Ghasemi-Nejhad, P. M. Ajayan, Super-compressible foamlike carbon nanotube films. *Science* **25**, 1307–1310 (2005).

69. S. Park, M. Vosguerichian, Z. Bao, A review of fabrication and applications of carbon nanotube film-based flexible electronics. *Nanoscale* **5**, 1727–1752 (2013).

70. S. Kivistö, T. Hakulin, A. Kaskela, B. Aitchison, D. P. Brown, A. G. Nasibulin, E. I. Kauppinen, A. Härkönen, O. G. Okhotnikov, Carbon nanotube films for ultrafast broadband technology. *Opt. Express* **17**, 2358–2363 (2009).

71. B. A. MacLeod, N. J. Stanton, I. E. Gould, D. Wesenberg, R. Ihly, Z. R. Owczarczyk, K. E. Hurst, C. S. Fewox, C. N. Folmar, K. H. Hughes, B. L. Zink, J. L. Blackburn, A. J. Ferguson, Large n- and p-type thermoelectric power factors from doped semiconducting single-walled carbon nanotube thin films. *Energ. Environ. Sci.* **10**, 2168–2179 (2017).

72. Y. Nakai, K. Hond, K. Yanagi, H. Kataura, T. Kato, T. Yamamoto, Y. Maniwa, Giant Seebeck coefficient in semiconducting single-wall carbon nanotube film. *Appl. Phys. Express* **7**, 025103 (2014).
73. D. Hayashi, Y. Nakai, H. Kyakuno, T. Yamamoto, Y. Miyata, K. Yanagi, Y. Maniwa, Improvement of thermoelectric performance of single-wall carbon nanotubes by heavy doping: Effect of one-dimensional band multiplicity. *Appl. Phys. Express* **9**, 125103 (2016).

74. A. Kosarev, S. Rumyantsev, M. Moreno, A. Torres, S. Boubanga, W. Knap, Si,Ge$_2$H-based microbolometers studied in the terahertz frequency range. *Solid State Electron.* **54**, 417–419 (2010).

75. S. A. Kuznetsov, A. G. Paulish, M. Navarro-Cía, A. V. Arzhannikov, Selective pyroelectric detection of millimetre waves using ultra-thin metasurface absorbers. *Sci. Rep.* **6**, 21079 (2016).

76. D. Y. Kim, K. O. Kenneth, Reduction of NEP variations for terahertz detectors using Schottky barrier diodes in CMOS. *Electron. Lett.* **53**, 732–734 (2017).

77. R. Huang, X. Ji, Y. Liao, J. Peng, K. Wang, Y. Xu, F. Yan, Dual-frequency CMOS terahertz detector with silicon-based plasmonic antenna. *Opt. Exp.* **27**, 23250–23261 (2019).

78. S. Suzuki, T. Nukariya, Y. Ueda, T. Otsuka, M. Asada, High current responsivity and wide modulation bandwidth terahertz detector using high-electronmobility transistor for wireless communication. *J. Infrared Millim. Terahertz Waves* **37**, 658–667 (2016).

79. Y. Kurita, G. Ducournau, D. Coquillat, A. Satou, K. Kobayashi, S. B. Tombet, Y. M. Meziani, V. V. Popov, W. Knap, T. Suemitsu, T. Otsuji, Ultrahigh sensitive sub-terahertz detection by InP-based asymmetric dualgrating-gate high-electron-mobility transistors and their broadband characteristics. *Appl. Phys. Lett.* **104**, 251114 (2014).

80. L. Dong, R. Yue, L. Liu, Fabrication and characterization of integrated uncooled infrared sensor arrays using a-Si thin-film transistors as active elements. *J. Microelectromech. Syst.* **14**, 1167–1177 (2005).

81. X. Yang, A. Vorobiev, A. Generalov, M. A. Andersson, J. Stake, A flexible graphene terahertz detector. *Appl. Phys. Lett.* **111**, 021102 (2017).
82. A. Paddubskaya, M. Demidenko, K. Batrakov, G. Valušis, T. Kaplas, Y. Svirko, P. Kuzhir, Tunable perfect THz absorber based on a stretchable ultrathin carbon-polymer bilayer. *Materials* **12**, 143 (2019).

83. T. Q. Trung, V. Q. Dang, H. B. Lee, D. Kim, S. Moon, N. E. Lee, H. Lee, An omnidirectionally stretchable photodetector based on organic—Inorganic heterojunctions. *ACS Appl. Mater. Interfaces* **9**, 35958–35967 (2017).

84. J. Ding, H. Fang, Z. Lian, Q. Lv, J. L. Sun, Q. Yan, High-performance stretchable photodetector based on CH$_3$NH$_3$PbI$_3$ microwires and graphene. *Nanoscale* **10**, 10538–10544 (2018).

85. J. Yoo, S. Jeong, S. Kim, J. H. Je, A stretchable nanowire UV–Vis–NIR photodetector with high performance. *Adv. Mater.* **27**, 1712–1717 (2015).

86. M. Kim, P. Kang, J. Leem, S. W. Nam, A stretchable crumpled graphene photodetector with plasmonically enhanced photoresponsivity. *Nanoscale* **9**, 4058–4065 (2017).