ACCOUNTS of chemical research

Article

Cite This: Acc. Chem. Res. 2019, 52, 523−533

pubs.acs.org/accounts

Flexible Electronics toward Wearable Sensing

Published as part of the Accounts of Chemical Research special issue "Wearable Bioelectronics: Chemistry, Materials, Devices, and Systems".

Wei Gao,*[,†] Hiroki Ota,*[,‡] Daisuke Kiriya,*[,§] Kuniharu Takei,*[,§] and Ali Javey*[,∥,⊥,#]

[†]Division of Engineering and Applied Science, California Institute of Technology, Pasadena, California 91125, United States

[‡]Department of Systems Integration, Yokohama National University, Yokohama 240-8501, Japan

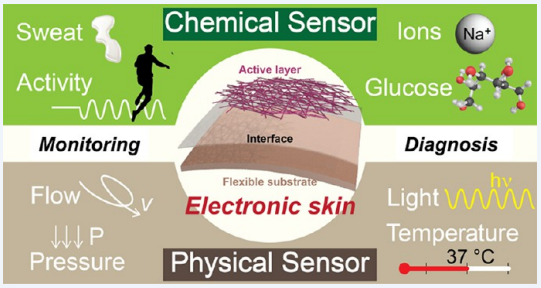
[§]Department of Physics and Electronics, Osaka Prefecture University, Osaka 599-8531, Japan

[∥]Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, California 94720, United States

[⊥]Berkeley Sensor and Actuator Center, University of California, Berkeley, California 94720, United States

[#]Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States

CONSPECTUS: Wearable sensors play a crucial role in realizing personalized medicine, as they can continuously collect data from the human body to capture meaningful health status changes in time for preventive intervention. However, motion artifacts and mechanical mismatches between conventional rigid electronic materials and soft skin often lead to substantial sensor errors during epidermal measurement. Because of its unique properties such as high flexibility and conformability, flexible electronics enables a natural interaction between electronics and the human body. In this Account, we summarize our recent studies on the design of flexible electronic devices and systems for physical and chemical monitoring. Material innovation, sensor design, device fabrication, system integration, and human studies employed toward continuous and noninvasive wearable sensing are discussed.



A flexible electronic device typically contains several key components, including the substrate, the active layer, and the interface layer. The inorganic-nanomaterials-based active layer (prepared by a physical transfer or solution process) is shown to have good physicochemical properties, electron/hole mobility, and mechanical strength. Flexible electronics based on the printed and transferred active materials has shown great promise for physical sensing. For example, integrating a nanowire transistor array for the active matrix and a conductive pressure-sensitive rubber enables tactile pressure mapping; tactile-pressure-sensitive e-skin and organic light-emitting diodes can be integrated for instantaneous pressure visualization. Such printed sensors have been applied as wearable patches to monitor skin temperature, electrocardiograms, and human activities. In addition, liquid metals could serve as an attractive candidate for flexible electronics because of their excellent conductivity, flexibility, and stretchability. Liquid-metal-enabled electronics (based on liquid−liquid heterojunctions and embedded microchannels) have been utilized to monitor a wide range of physiological parameters (e.g., pulse and temperature).

Despite the rapid growth in wearable sensing technologies, there is an urgent need for the development of flexible devices that can capture molecular data from the human body to retrieve more insightful health information. We have developed a wearable and flexible sweat-sensing platform toward real-time multiplexed perspiration analysis. An integrated iontophoresis module on a wearable sweat sensor could enable autonomous and programmed sweat extraction. A microfluidics-based sensing system was demonstrated for sweat sampling, sensing, and sweat rate analysis. Roll-to-roll gravure printing allows for mass production of high-performance flexible chemical sensors at low cost. These wearable and flexible sweat sensors have shown great promise in dehydration monitoring, cystic fibrosis diagnosis, drug monitoring, and noninvasive glucose monitoring.

Future work in this field should focus on designing robust wearable sensing systems to accurately collect data from the human body and on large-scale human studies to determine how the measured physical and chemical information relates to the individual's specific health conditions. Further research in these directions, along with the large sets of data collected via these wearable and flexible sensing technologies, will have a significant impact on future personalized healthcare.

1. INTRODUCTION

Wearable electronics are expected to play a crucial role in personalized medicine as they continuously and closely monitor an individual's physical activities and health status. Because of its high flexibility and conformability, flexible electronics could serve as an ideal platform for designing future personalized wearable devices.[1−4] Emerging nanotechnology and materials

Received: October 1, 2018
Published: February 15, 2019

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

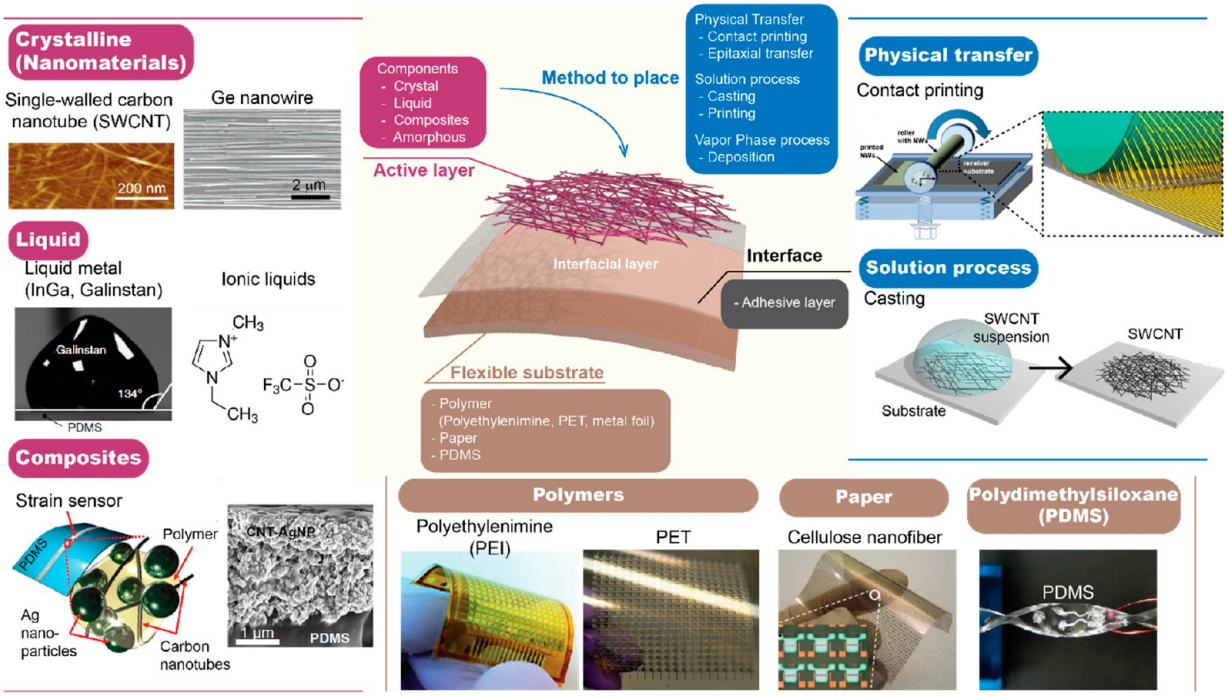


Figure 1. Materials of electronic skin toward wearable physical and chemical sensing. The devices are constructed from the substrates, the active layers for functionalization, and the adhesive layer to keep the active layer attached to the substrate. The transfer method should be considered to construct the active layer. Reproduced with permission from refs 9, 11, 14, 16, 24, 25, and 28. Copyright 2009 Wiley, 2014 National Academy of Sciences, 2014 American Chemical Society, 2014 Nature Publishing Group, 2014 Wiley, 2015 Wiley, and 2013 Nature Publishing Group, respectively.

science have recently led to remarkable development in flexible electronics for personalized healthcare. In this Account, we focus on the very recent advances in flexible electronics from our group for both physical and chemical sensing. In the following sections, we review material innovation, device fabrication, sensor design, and system integration employed toward noninvasive wearable sensing systems. Finally, the overall challenges and opportunities that lie ahead for flexible electronic skin on the road toward personalized health monitoring are discussed.

2. MATERIALS AND DEVICE FABRICATION

Figure 1 illustrates a typical configuration of a flexible electronic device: the key components are the substrate, the active layer, and the interface layer between them. The substrate is the base to build up devices, the active layer includes materials or electrical circuits to add functionalities, and the interface is important in some cases to keep the active layer on or inside the substrate (e.g., adhesion of SWCNTs on substrates shown below). These layers should be well-designed for the designated targets.

The active layer, composed of materials or electrical components on the e-skin to add functionalities, is critical for constructing the device on the flexible substrate. Organic materials have been widely explored as flexible device materials.[5] In contrast, inorganic nanomaterials have good physicochemical properties, high electron/hole mobility, chemical durability, and mechanical strength; they can also be applied as an active material to construct flexible devices through standard lithography processes. For example, carbon nanotubes (CNTs)[6] and graphene[7] have been utilized as active layers in field-effect transistors (FETs) and sensors, and semiconducting crystalline nanowires show high performance as FETs on flexible substrates.[8−10] Composite materials (e.g., CNT−Ag nanoparticle (AgNP) composites) can also be applied as active conductive layers on flexible and stretchable substrates.[11] To achieve effective construction of the active layer, the interface layer between the active layer and the substrate is also critical, especially for FET operation (Figure 1). In the case of single-walled carbon nanotube (SWCNT) metal−oxide−semiconductor FETs (MOSFETs), the interface is critical to achieve gate controllability.[12,13] A thin single-layer network of SWCNTs is required to control the electrostatic operation of the MOSFET, which is obtained only when SWCNTs and the substrate are in an attractive condition on the designed interface layer.[14] Because of their excellent conductivity, flexibility, and stretchability, liquid metals are expected to enable conformal coverage on curved and soft surfaces of electronic systems that will have applications in wearable sensors, robotics, and prosthetics.[15] Gallium metal alloys, particularly eutectic gallium indium (EGaIn) and Galinstan (Ga/In/Sn), are among the most widely used liquid metals in electrical components, including electrodes and sensors (Figure 1).[16] They are ideal materials for designing a stretchable and flexible electronic skin. Under extreme stretching, twisting, and bending, unlike contacts based on solid metals and polymers, which will experience cracking or disconnection, the liquid metal electrodes and interconnections can act as a "self-healing" wire and maintain good electrical performance because of their fluidity.[17−20]

The choice for the process of transferring the active layer onto the substrate is dependent on the preparation process for the materials of the active layers. As illustrated in Figures 2 and 3, physical transfer and solution processes have been explored. In the physical transfer method, nanowires directly contact the substrate and are transferred in an aligned manner (Figure 2). For example, Ge nanowires grown vertically on flat donor substrates can be transferred via mechanical shearing to an acceptor substrate (Figure 2a),[9] or Ge nanowires grown on a

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

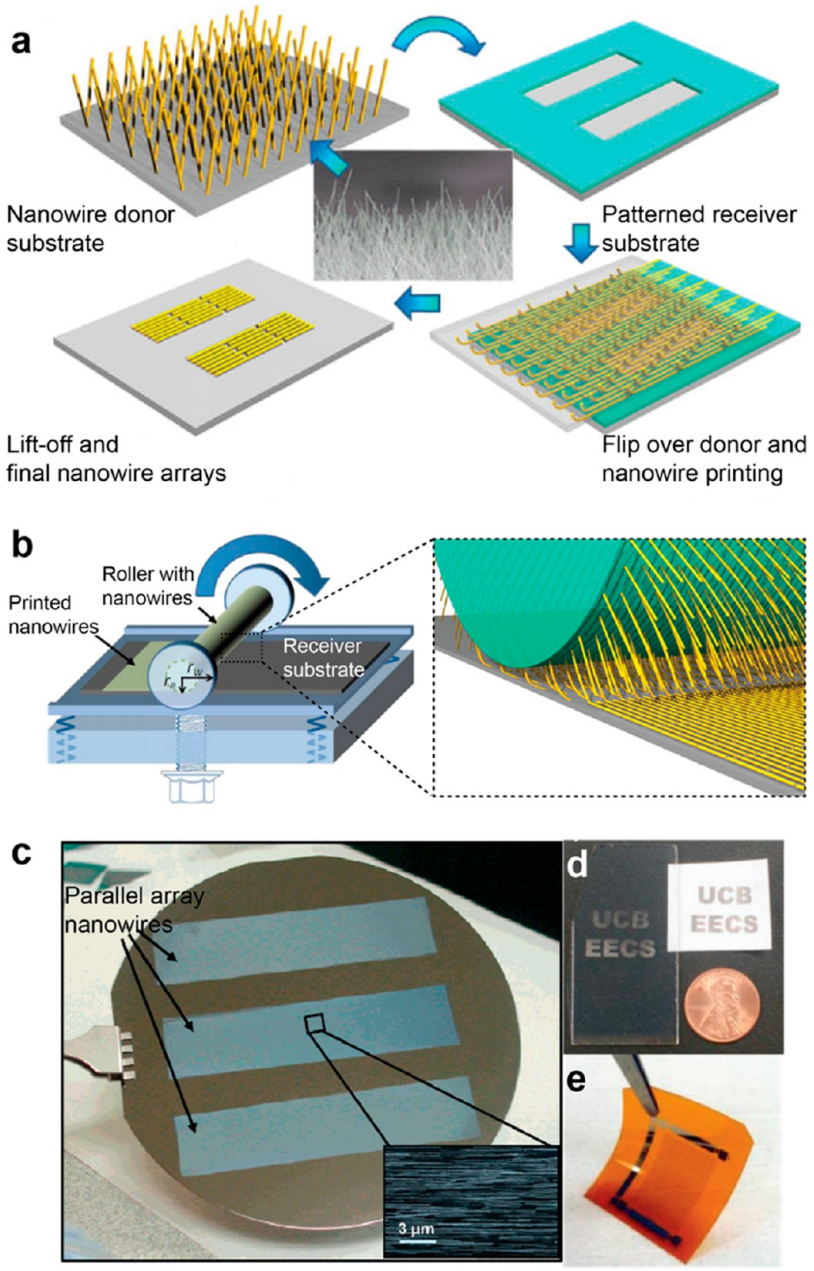


Figure 2. Physical transfer of nanowires. (a) Transfer of Ge nanowires via contact shearing. (b) Illustrative image of roll-contact printing. (c–e) Images of nanowire-transferred (c) wafer, (d) glass and paper, and (e) flexible polyimide substrates. Reproduced with permission from ref 9. Copyright 2009 Wiley.

roller can be transferred to the substrate via mechanical roll contact (Figure 2b).[9,21] These nanowire arrays can be patterned with further photolithography and lift-off processes. Nanowire arrays were realized on a 4 in. wafer, glass, paper, and a flexible polyimide substrate (Figure 2c-e), and showed high optoelectronic performance.[8,22] By means of electrostatic and van der Waals interaction forces, the nanowires can be transferred onto any surface, including flexible substrates. These uniform-nanowire active layers can serve as high-mobility transistor channels to construct e-skins.

Solution transfer processes have been widely applied to construct active layers for flexible electronics because of their lower temperature and greater suitability for mass-production printing technology.[23−25] To form a printable ink by mixing nanomaterials and organic materials, wettability and adhesion of inks on the targeted surface should be considered.[11,14] SWCNT solutions were developed as printable inks. It is inevitable to consider that SWCNTs are wrapped with surfactants to prohibit aggregation in the solution (ink); therefore, to effectively form the active layer, the design of the interaction between the surfactant and the substrate is critical (Figure 3a,b).[12,14] In order to assemble an FET-grade SWCNT network, the areal density of the randomly deposited SWCNTs should be higher than the percolation limit between electrodes.[26] Furthermore, it should be a sufficiently thin single layer; otherwise, it is difficult to modulate carriers to operate FETs because of the metallic behavior of bundled SWCNTs. An effective deposition method was developed using cholate surfactants, such as sodium cholate (SC), to prepare SWCNT inks combined with the designed substrate modified with amine-terminated interlayers, such as

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

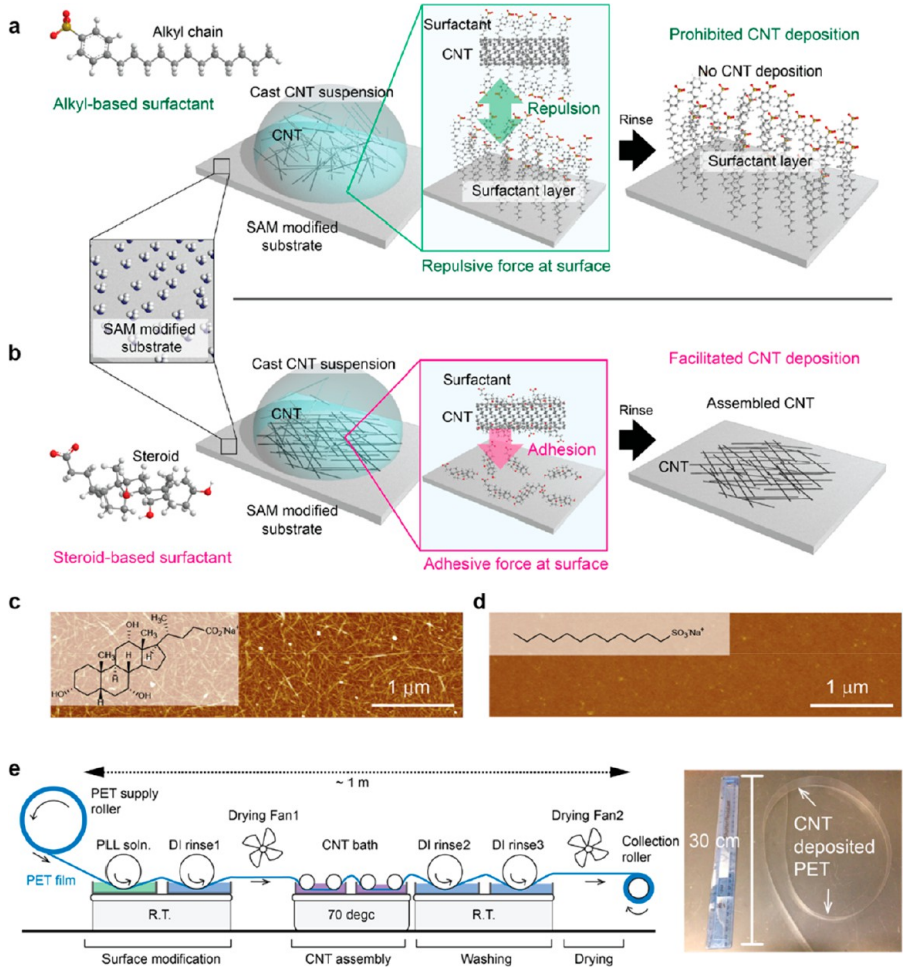


Figure 3. Solution process to transfer SWCNTs. (a) An alkyl-chain-type interlayer (surfactant) shows no deposition and (b) a cholate-type interlayer (surfactant) shows effective assembly of SWCNTs. (c, d) Atomic force microscope images of the interlayer (surfactant) of (c) sodium cholate and (d) sodium dodecyl sulfate. (e) Roll-to-roll printing of SWCNTs. Reproduced from ref 14. Copyright 2014 American Chemical Society.

poly-L-lysine (PLL) and (3-aminopropyl)triethoxysilane (APTES). The design of the SC surfactant and the amine-terminated interlayer facilitates the assembly of SWCNTs and achieves over 90% effective coverage (Figure 3c). On the other hand, the ability of alkyl-chain-based surfactants to disperse SWCNTs in an ink yielded poor assembly on the PLL-modified surface (Figure 3d). As a result, the combination of the SC surfactant and amine-terminated interlayer method is effective to assemble SWCNTs quickly, and roll-to-roll printing of the active layer of the SWCNT network on a poly(ethylene terephthalate) (PET) substrate was demonstrated at a scale of over 1 m in length (Figure 3e).

3. FLEXIBLE ELECTRONICS FOR PHYSICAL SENSING

The active printed or transferred materials discussed above have been widely used in the e-skin platform for physical sensing. Applications include strain and temperature sensors,[25,27,28] electronic whiskers (e-whiskers),[11,29] and wearable devices.[30]

For the active matrix backplane of the e-skin, nanomaterial-based transistor arrays using aligned nanowire arrays[27] or SWCNT network films[12] have been patterned for the switching function to select each pixel for tactile pressure readings. Figure 4a displays an e-skin based on aligned Ge/Si core/shell nanowire array transistors, where the nanowire arrays are used as the transistor channel.[27] The transistors show a relatively high field-effect mobility of ~20 cm^2 V^{-1} s^{-1} with an ON/OFF current ratio of about 100. Importantly, the transistors are mechanically stable even under a 2.5 mm bending radius and >2000 bending cycles. Integrating a nanowire transistor array (18 × 19 pixels) for the active matrix and a conductive pressure-sensitive rubber (PSR) (Figure 4c) enables tactile pressure mapping similar to that of human skin (Figure 4d). Although the conductive-type PSR was used for this application, other types of PSR using the mechanism of capacitance change or piezoelectric detection can be also applied to the e-skin.[31]

In addition to sensing, user-interactive functionalities are highly attractive for future electronic skins. Tactile-pressure-sensitive e-skins and organic light-emitting diodes (OLEDs) can be integrated for instantaneous pressure visualization (Figure 4e).[28] An active matrix circuit consisting of an SWCNT network thin-film transistor with a field-effect mobility of ~20 cm^2 V^{-1} s^{-1} was used to read the tactile pressure on each pixel (Figure 4g,h). The emitted peak wavelength of the OLED can be adjusted by changing the organic emissive material. The device configuration was 16 × 16 pixels, where each pixel has an SWCNT transistor, a PSR, and an OLED. As shown in Figure 4j,k, the OLEDs emit light when sufficient tactile pressure is applied over the pixel as a result of the conductivity change of the PSR and the corresponding current change through the OLED.

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

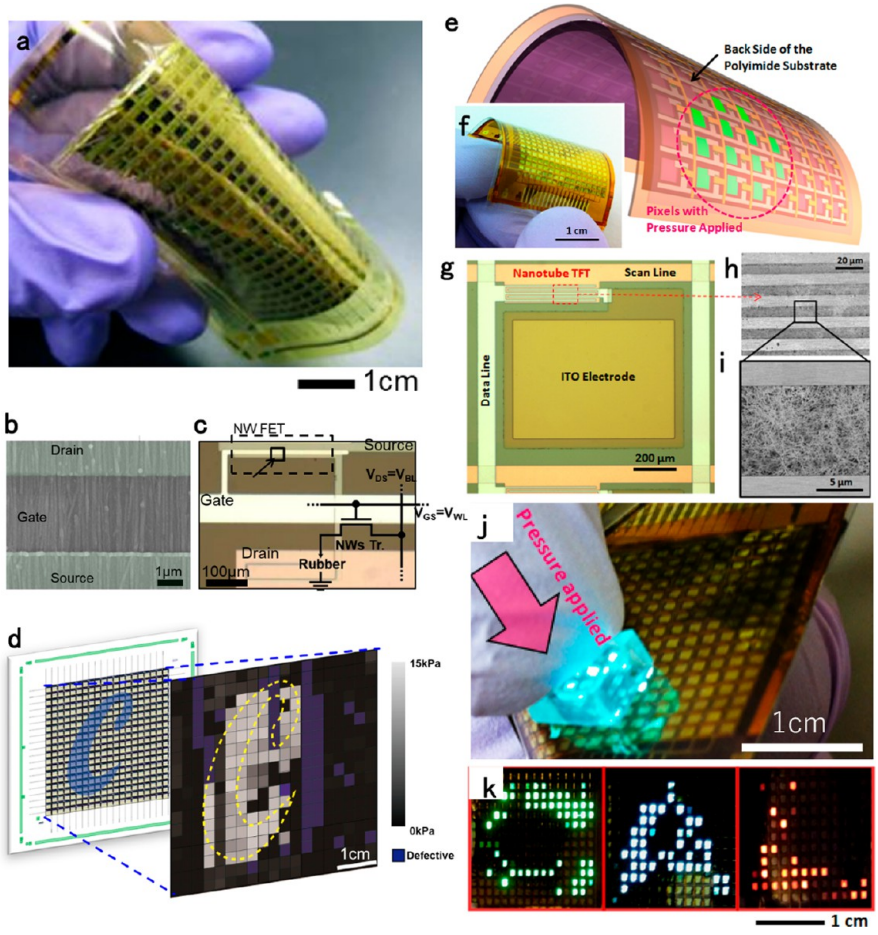


Figure 4. Interactive electronic skin. (a) Photo of the Ge/Si core/shell nanowire array-based active matrix e-skin. (b) Scanning electron microscopy (SEM) image of the aligned nanowire array in the transistor channel and (c) photo of the pixel. The inset shows the circuit diagram of the pixel. (d) Tactile pressure mapping results. Reproduced with permission from ref 27. Copyright 2010 Nature Publishing Group. (e) Schematic and (f) photo of the tactile-responsive e-skin. (g) Photo of a pixel and (h, i) enlarged SEM images of the SWCNT network transistor channels. (j) Light-emissive responsive e-skin demonstration. (k) Green-, blue-, and red-light-emissive displays due to applying tactile pressure. Reproduced with permission from ref 28. Copyright 2013 Nature Publishing Group.

The e-skin devices explained above are typically fabricated by standard photolithography and vacuum-based deposition techniques. For practical applications, macroscale flexible electronics, including e-skins, should be economically prepared on a large scale. In this regard, printing techniques such as screen printing and gravure printing hold great promise for future flexible electronics. The fully printed 20 × 20 array CNT-based active matrix backplane integrated with a tactile-pressure sensor on a PET film was demonstrated via a roll-to-plate gravure printing method.[25] The transistor performances were 4 ± 2 μA/mm, 4 ± 0.4, and 0.8 ± 0.3 cm^2 V^{-1} s^{-1} for the on current normalized by the width, $\log(I_{ON}/I_{OFF})$, and field-effect mobility, respectively. Such a printing technology is critical to demonstrate macroscale electronic skin toward flexible and wearable sensing.

Figure 5a–c shows printed strain sensors, i.e., electronic whiskers (e-whiskers), obtained using a mixture of a CNT paste and a AgNP ink on a polydimethylsiloxane (PDMS) film.[11] The strain-sensing mechanism monitors the tunneling current between AgNPs, as described in Figure 5c.[29] When the film is deformed, the distance between the AgNPs increases as a result of the tensile strain on the top surface of the PDMS film, resulting in a lower tunneling current. The electrical resistance of the strain-sensing film increases (decreases) when the resistive-change sensitivity is ∼8% Pa^{-1} under tensile (compressive) strain caused by nitrogen (N_2) gas flow (Figure 5d). Next, seven e-whiskers were attached to a semispherical PDMS object with printed Ag interconnect electrodes (Figure 5e). Under a flow of N_2 gas from one side, the gas flow distribution can be successfully monitored by the e-whisker array (Figure 5f). It should be noted that there are different approaches to demonstrate highly sensitive strain or tactile sensors using carbon nanomaterials (CNTs, graphene, etc.) arranged by the device structures such as network or foam shapes.[4,32,33]

Such printed sensors can be applied as wearable healthcare patches. Figure 5g shows printed flexible strain sensors (functioning as a three-axis accelerator) screen-printed on a PET film along with electrocardiogram (ECG), skin temperature, and UV sensors.[30] Here the ECG sensor was made of screen-printed Ag electrodes. The temperature sensor consisted of a mixture of CNTs and poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS). The UV sensor was made of a ZnO nanorod network thin film. Attaching the wearable device onto skin allows the UV light intensity, skin temperature, ECG signals, and human activities to be monitored simultaneously (Figure 5h).

As another type of pressure and strain sensors, liquid-metal-based devices have been developed.[17,20] As shown in Figure 6a, a

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523–533

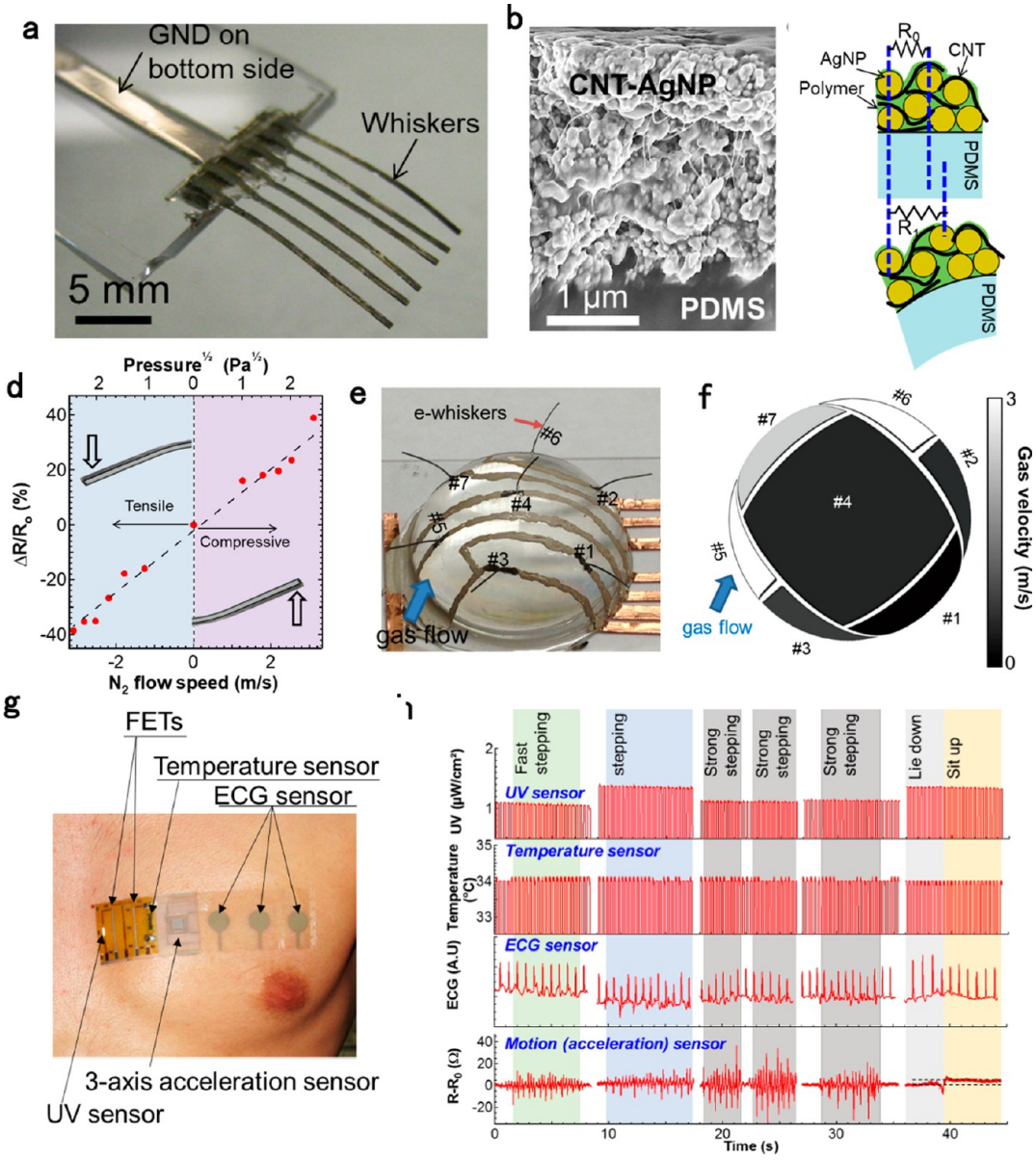


Figure 5. Flexible electronic devices for pressure sensing. (a) Fully printed artificial electronic whiskers. (b) SEM images of the CNTs and the AgNP composite film of the strain sensor. (c) Strain -sensing mechanism. (d) Normalized resistance change ratio as a function of the N_2 gas flow rate and pressure. (e) Demonstration of an e-whisker array and (f) gas flow distribution mapping result. Reproduced with permission from ref 11. (g) Flexible healthcare patch sheet and (h) real-time multiple sensing results of UV, skin temperature, ECG, and human motion. Reproduced from ref 30.

soft tactile diaphragm pressure sensor based on microfluidic channels filled with Galinstan was developed.[17] The diaphragm pressure sensor design utilized a Wheatstone bridge circuit to measure small resistance changes caused by the applied pressure. The device had an ultralow detection limit below 100 Pa and was able to sense sub-50 Pa changes in pressure (Figure 6b). Furthermore, the Wheatstone bridge embedded in the diaphragm pressure sensor also provided temperature self-compensation in the operation range of 20−50 °C, which is critical for practical use considering that the temperature could have a significant influence on the performance of resistive pressure sensors. The applications of such a pressure sensor toward wearable sensing were demonstrated in the context of real-time heart rate monitoring via a PDMS wristband and tactile sensing via a PDMS glove.

In order to realize liquid-state devices and systems, different liquid components are required for controlled heterojunctions (Figure 6c),[16] analogous to the metal−semiconductor or semiconductor−semiconductor junctions seen in conventional solid-state devices. In a liquid−liquid heterojunction, it is critical to prevent the breakdown of liquid heterointerfaces. On the basis of these considerations, a system for temperature and humidity sensing (Figure 6d) using Galinstan with highly robust liquid-state heterojunctions was developed.[16] The use of this liquid-state heterojunction and the ionic liquid as active sensing elements greatly expands the species of the liquid-state sensor.

Adding two-dimensional (2D) fabrication methods such as soft lithography to a three-dimensional (3D) printing method with liquid metals realizes good system-level fabrication methods toward physical sensing (Figure 6e).[18] One of the advantages of applying liquid metals as electrodes is easy fabrication of electrical interconnections in three dimensions with a stable contact between the electrodes and electrical components in solid-state electronics such as integrated circuits,

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

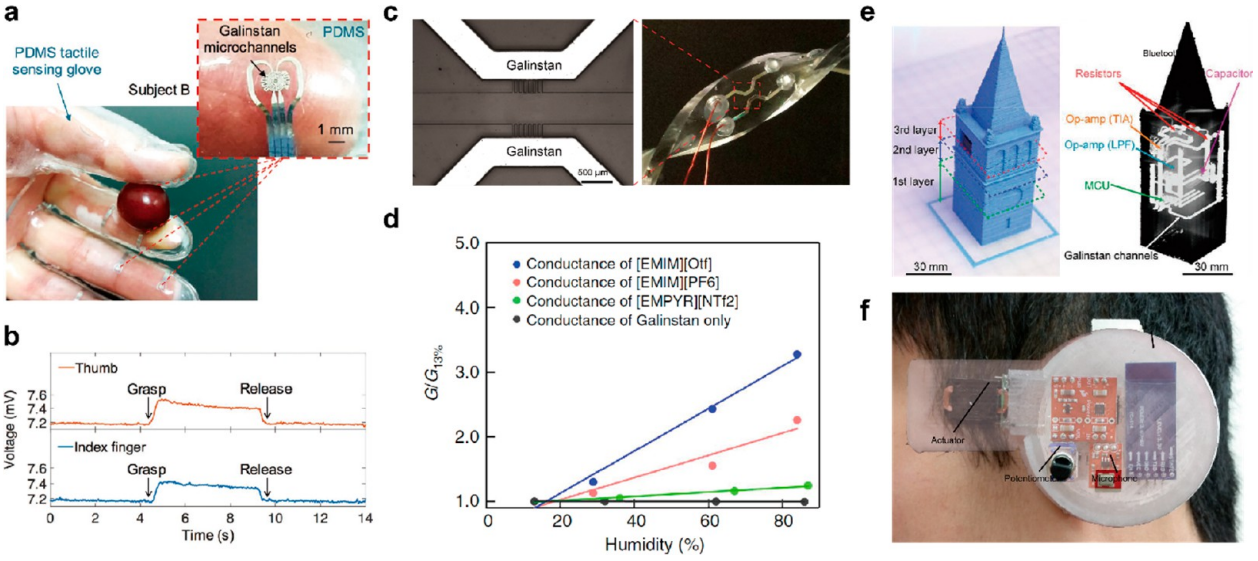


Figure 6. Liquid-metal-based flexible electronics for wearable sensing. (a) Microfluidic tactile diaphragm pressure sensor. (b) Real-time pressure sensing response recorded during gentle grasp and release. Reproduced with permission from ref 17. Copyright 2017 Wiley. (c) Liquid-state heterojunction sensor. (d) Humidity sensor using liquid-state heterojunctions. Reproduced with permission from ref 16. Copyright 2014 Nature Publishing Group. (e) Optical and X-ray images of a 3D-printed photodetection system. Reproduced with permission from ref 18. Copyright 2016 Wiley. (f) 3D-printed "earable" device for core body temperature detection with Galinstan electrodes and interconnects. Reproduced from ref 19. Copyright 2017 American Chemical Society.

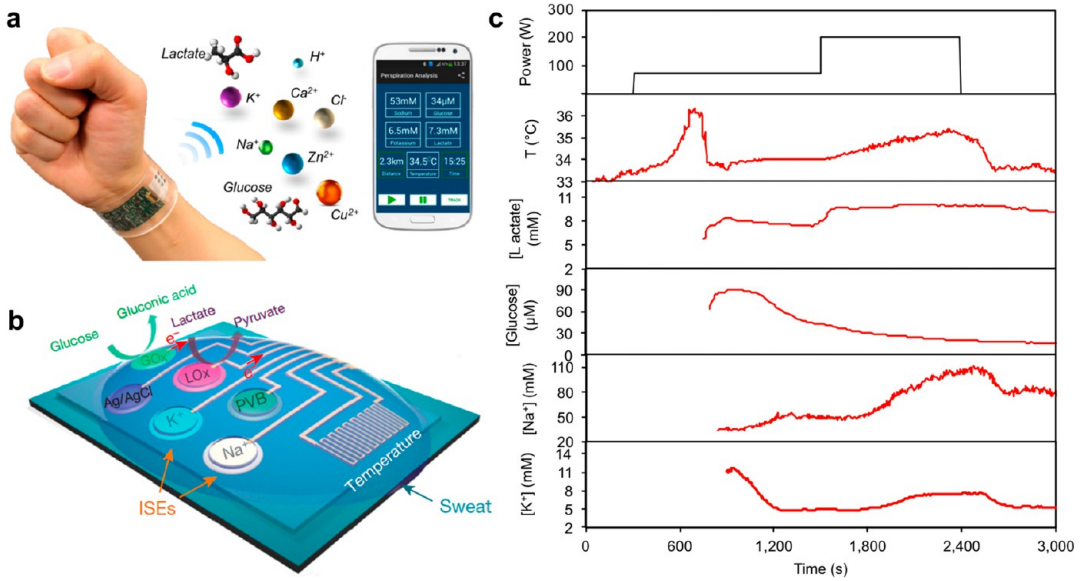


Figure 7. Wearable sweat sensor. (a) Fully integrated flexible sweat sensor array. (b) Schematic of a sensor array for monitoring of sweat metabolites and electrolytes. (c) Real-time sweat analysis during a cycling exercise. Reproduced with permission from ref 37. Copyright 2016 Nature Publishing Group.

resistors, and capacitors. In terms of liquid metal interconnections, only injections of liquid metals are required as long as the circuit designs of the microchannels for electrodes are optimized. A monolithic printed smart glove with a resistive heater and an "earable" core body temperature sensor (Figure 6f) based on 3D embedded liquid metal microchannels were demonstrated.[19]

4. FLEXIBLE ELECTRONICS FOR WEARABLE CHEMICAL SENSING

As most of the skin-interfaced flexible sensors reported to date primarily focused on monitoring of the user's physical activities and vital signs, there is a strong need for the development of flexible devices that can capture molecular data from the human body to retrieve more insightful health information. In traditional clinical or laboratory settings, health examinations rely heavily on blood analysis, which is limited by invasive blood draws that cannot provide dynamic and continuous information. Human sweat is an important and easily accessible body fluid containing a wealth of chemicals that can reflect an individual's physiological state.[34−42] It has been shown that abnormal health conditions can significantly affect sweat composition by varying the concentrations of sweat analytes.[37,39−41] The transition from blood analysis to in situ sweat analysis via a wearable sweat

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

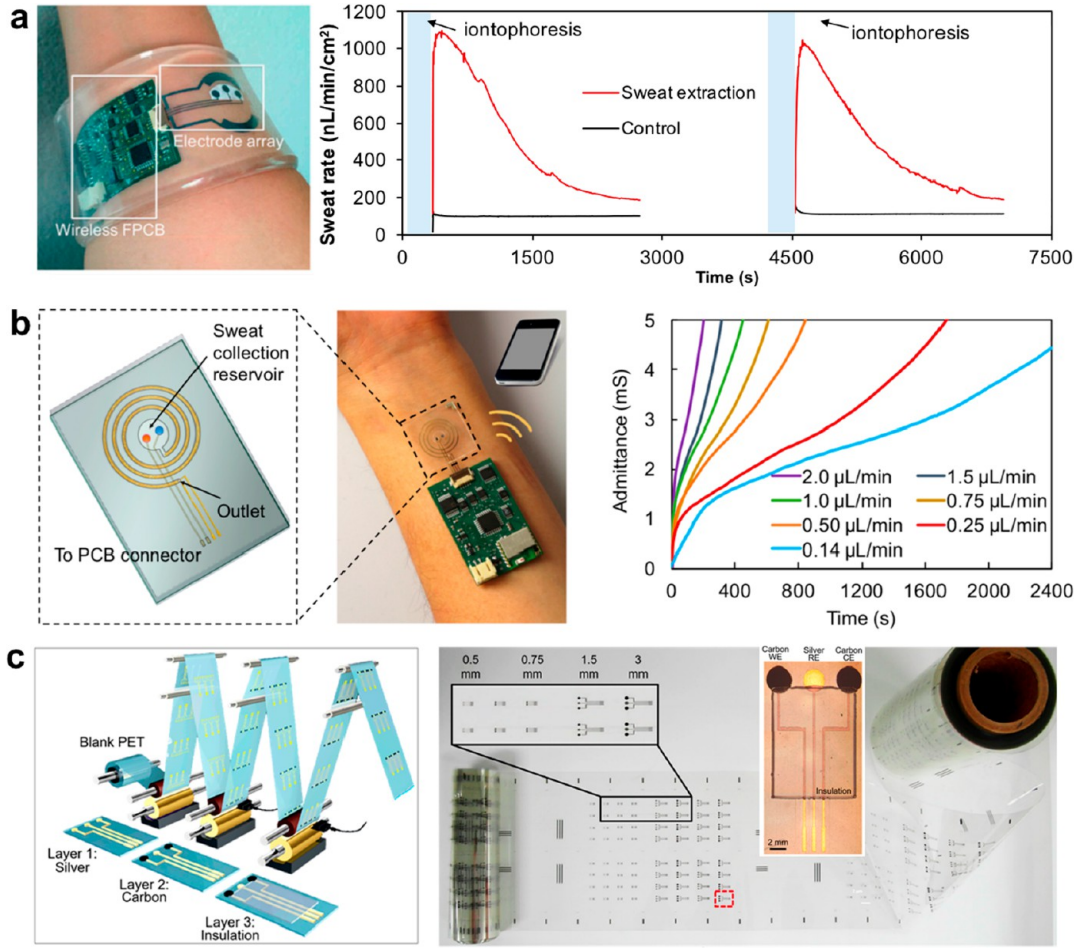


Figure 8. Effort toward enhancing sweat induction, sampling, and sensing. (a) Wearable sensor with an integrated iontophoresis module toward autonomous sweat extraction. Reproduced with permission from ref 41. (b) Microfluidics-based sensing system for sweat sampling, sensing, and sweat rate analysis. Reproduced from ref 45. Copyright 2018 American Chemical Society. (c) Roll-to-roll gravure printing enabled mass production of high-performance flexible chemical sensors at low cost. Reproduced from ref 47. Copyright 2018 American Chemical Society.

sensor could provide a noninvasive and attractive means of dynamic health assessment.[34−42]

A number of wearable and flexible sweat sensors have recently been developed toward continuous health monitoring. Given the complex sweat secretion process, multiplexed and real-time detection of target biomarkers of interest is in urgent need. We proposed an integrated wearable and flexible sensor array for in situ sweat sensing.[37] This skin patch consists of multiple high-performance electrochemical sensors and a flexible printed circuit board (FPCB) for signal processing and wireless transmission. This device simultaneously measures sweat metabolites (lactate and glucose) and sweat electrolytes (Na^+ and K^+) as well as skin temperature (Figure 7).[37] The wearable system was able to monitor changes in physiologically relevant analytes over periods of prolonged exercise. The scope of this platform was later expanded to monitor a wide panel of analytes, including pH, Ca^{2+}, Cl^-, heavy metals, and other substances.[41−46]

While sweat is easily accessible during vigorous physical exercise, its composition varies as the body undergoes fast physiological and metabolic changes. To this end, for medical applications, a promising sweat induction method is iontophoresis, which could be used to induce sweat excretion locally via chemical stimulation of the sweat gland. During iontophoresis, a small electric current is applied to pass the charged substance (e.g., pilocarpine, acetylcholine, or methacholine) through intact skin, which stimulates the secretion of sweat. A flexible sweat extraction and analysis platform has recently been demonstrated that contains a chemically enhanced iontophoresis module capable of autonomously inducing sweat (Figure 8a).[41] Through programming of the drug concentrations in iontophoresis hydrogels and the iontophoresis period, various sweat secretion profiles can be achieved. The integrated chemical sensors between the iontophoresis electrodes can perform in situ analysis of the extracted sweat analytes.

It has been widely recognized that sweat composition and sweat rate are inextricably linked.[34,36,40] In this regard, sweat rate monitoring will be crucial for both fundamental and clinical investigations. A flexible microfluidic sweat-sensing patch has recently been developed for real-time sweat rate monitoring and enhanced sweat analysis (Figure 8b).[45] The magnitude of the electrical impedance between two parallel electrodes in the microchannel drops as sweat fills the microchannel. The sweat rate could be calculated as the change in sweat volume in the channel divided by the time interval. The use of microfluidic systems can minimize the sweat evaporation and contamination, resulting in more accurate sweat sensing with higher temporal resolution.

In practical health monitoring applications, high-throughput and low-cost fabrication of flexible sensors with high stability

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

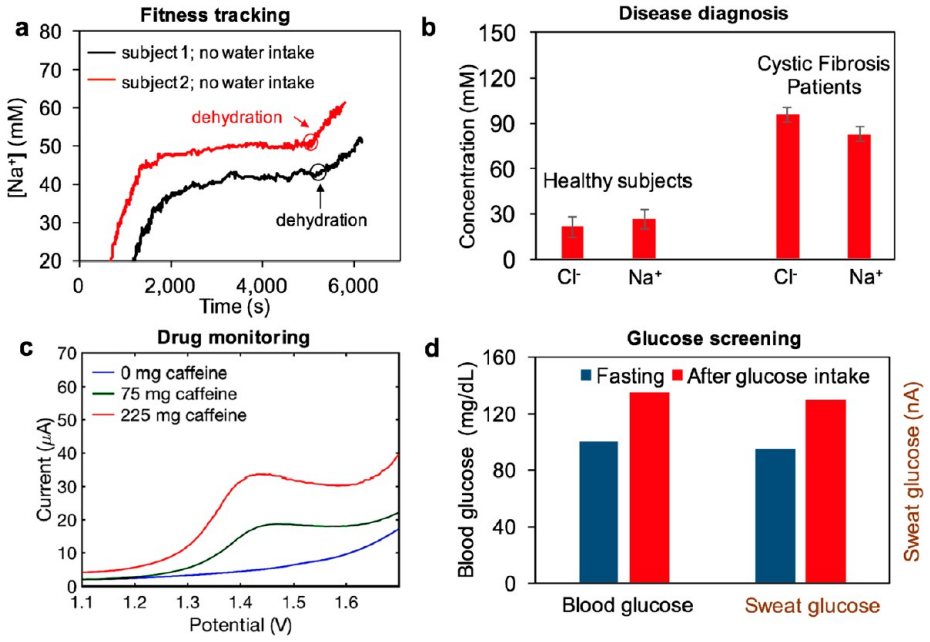


Figure 9. Physiological and biomedical applications of wearable and flexible sweat sensors. (a) Dehydration monitoring during physical exercise. Reproduced with permission from ref 37. Copyright 2016 Nature Publishing Group. (b) Screening and diagnosis of cystic fibrosis. Reproduced with permission from ref 41. (c) Dynamic drug (i.e., caffeine) monitoring. Reproduced with permission from ref 46. Copyright 2018 Wiley. (d) Correlation study of sweat and blood glucose levels toward noninvasive glucose monitoring. Reproduced with permission from ref 41.

and reproducibility is critical for the commercial adoption of future wearable sensors.[47,48] In this regard, roll-to-roll (R2R) gravure printing technology has been exploited to print high-performance flexible sensing electrodes on 150 m flexible substrate rolls (Figure 8c).[47] These electrodes can be used to prepare flexible sensors for analyzing sweat metabolites, ions, and other substances. Such R2R gravure printing technology represents a significant step in enabling low-cost mass production of future wearable and flexible sensors.

The development of wearable sweat sensors opens the door to physiological and biomedical monitoring applications. We recently showed that such wearable sensors could potentially be used for real-time monitoring of dehydration during prolonged physical exercise (Figure 9a).[37] Sweat Na^+ levels remained stable during euhydration trials, while substantial increases in sweat Na^+ levels were observed when the subjects had lost a large amount of water during the outdoor running. The use of the sweat sensor for cystic fibrosis screening and early diagnosis was successfully demonstrated by detection of elevated sweat electrolyte (Na^+ and Cl^-) levels (Figure 9b).[41] Wearable sweat sensors have been shown to have great promise in dynamic drug monitoring for precision medicine. Elevated caffeine levels in sweat with increasing drug dosage and confirmable caffeine physiological trends were observed (Figure 9c).[46] The wearable devices allow investigation of the dynamic correlation between sweat and blood analyte levels. Our preliminary data showed that oral glucose consumption resulted in an increase in sweat glucose level for most of the fasting subjects (Figure 9d).[41]

5. CONCLUSION AND OUTLOOK

In this Account, we have reviewed and highlighted the latest scientific and technical advances in flexible electronic devices toward wearable physical and chemical sensing. Such skin-interfaced flexible sensors have promising prospects in personalized healthcare, as they provide affordable and non-invasive solutions for health monitoring, early diagnosis, and disease management beyond traditional controlled laboratory settings. Despite the significant progress, a major hurdle in this field is the lack of robust wearable sensing systems that can accurately and continuously collect data from the human body. Novel materials, sensing techniques, and seamless system integration strategies need to be explored in order to realize the full potential of flexible electronics toward wearable sensing. Future work should also focus on human studies to determine how the measured physical and chemical information relates to the individual's health status. Considering the complexity of the human body, skin-interfaced flexible systems that can monitor both biomolecular levels and vital signs (e.g., blood pressure, heart rate, respiratory rate, and body temperature) represent an attractive solution for accurately predicting and identifying more specific health conditions. Further research in these directions, along with the large sets of data collected from population studies via these wearable sensing technologies, will have a significant impact on personalized healthcare.

AUTHOR INFORMATION

Corresponding Authors

*E-mail: ajavey@berkeley.edu (A.J.).
*E-mail: weigao@caltech.edu (W.G.).
*E-mail: ota-hiroki-xm@ynu.ac.jp (H.O.).
*E-mail: kiriya@pe.osakafu-u.ac.jp (D.K.).
*E-mail: takei@pe.osakafu-u.ac.jp (K.T.).

ORCID

Daisuke Kiriya: 0000-0003-0270-3888
Kuniharu Takei: 0000-0001-9166-3747
Ali Javey: 0000-0001-7214-7931

Notes

The authors declare no competing financial interest.

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533

Biographies

Wei Gao received his Ph.D. degree in Chemical Engineering from the University of California, San Diego, in 2014 and performed his postdoctoral work at the University of California, Berkeley, between 2014 and 2017. He is currently an assistant professor of medical engineering at California Institute of Technology. His research focuses on biosensors, flexible electronics, and micro/nanomachines.

Hiroki Ota received his Ph.D. degree in Mechanics at Keio University in Japan in 2011 and performed his postdoctoral work at the Tokyo Women's Medical University–Waseda University Joint Institution for Advanced Biomedical Sciences and the University of California, Berkeley. He is currently an associate professor at Yokohama National University. His current research focuses on flexible sensors/actuators using liquid metals and smart devices for healthcare.

Daisuke Kiriya received his Ph.D. degree in Engineering from Kyoto University in Japan in 2009 and performed his postdoctoral work at the University of Tokyo from 2009 to 2012 and the University of California, Berkeley, between 2012 and 2016. He is currently an assistant professor in the Department of Physics and Electronics at Osaka Prefecture University in Japan. His research focuses on molecular modification of nanomaterials and 2D material devices.

Kuniharu Takei received his Ph.D. degree in 2009 from Toyohashi University of Technology in Japan and performed his postdoctoral work at the University of California, Berkeley, between 2009 and 2013. He is currently an associate professor in the Department of Physics and Electronics at Osaka Prefecture University in Japan. His research focuses on flexible printed electronics and device physics.

Ali Javey received his Ph.D. degree in chemistry from Stanford University in 2005 and was a Junior Fellow of the Harvard Society of Fellows from 2005 to 2006. He then joined the faculty of the University of California, Berkeley, where he is currently a professor of Electrical Engineering and Computer Sciences. He is also a faculty scientist at the Lawrence Berkeley National Laboratory, where he serves as the program leader of Electronic Materials (E-Mat). He is an associate editor of *ACS Nano*.

REFERENCES

(1) Rogers, J. A.; Someya, T.; Huang, Y. Materials and mechanics for stretchable electronics. *Science* **2010**, *327*, 1603–1607.

(2) Someya, T.; Bao, Z.; Malliaras, G. G. The Rise of Plastic Bioelectronics. *Nature* **2016**, *540*, 379–385.

(3) Kim, D.-H.; Lu, N.; Ma, R.; Kim, Y.-S.; Kim, R.-H.; Wang, S.; Wu, J.; Won, S. M.; Tao, H.; Islam, A.; Yu, K. J.; Kim, T.-i.; Chowdhury, R.; Ying, M.; Xu, L.; Li, M.; Chung, H.-J.; Keum, H.; McCormick, M.; Liu, P.; Zhang, Y.-W.; Omenetto, F. G.; Huang, Y.; Coleman, T.; Rogers, J. A. Epidermal Electronics. *Science* **2011**, *333*, 838–843.

(4) Lipomi, D. J.; Vosgueritchian, M.; Tee, B. C.; Hellstrom, S. L.; Lee, J. A.; Fox, C. H.; Bao, Z. Skin-Like Pressure and Strain Sensors Based on Transparent Elastic Films of Carbon Nanotubes. *Nat. Nanotechnol.* **2011**, *6*, 788–792.

(5) Lüssem, B.; Keum, C.-M.; Kasemann, D.; Naab, B.; Bao, Z.; Leo, K. Doped Organic Transistors. *Chem. Rev.* **2016**, *116*, 13714–13751.

(6) Chen, K.; Gao, W.; Emaminejad, S.; Kiriya, D.; Ota, H.; Nyein, H. Y. Y.; Takei, K.; Javey, A. Printed Carbon Nanotube Electronics and Sensor Systems. *Adv. Mater.* **2016**, *28*, 4397–4414.

(7) Kim, K. S.; Zhao, Y.; Jang, H.; Lee, S. Y.; Kim, J. M.; Kim, K. S.; Ahn, J. H.; Kim, P.; Choi, J. Y.; Hong, B. H. Large-Scale Pattern Growth of Graphene Films for Stretchable Transparent Electrodes. *Nature* **2009**, *457*, 706–710.

(8) Takahashi, T.; Takei, K.; Adabi, E.; Fan, Z.; Niknejad, A. M.; Javey, A. Parallel Array InAs Nanowire Transistors for Mechanically Bbendable, Ultrahigh Frequency Electronics. *ACS Nano* **2010**, *4*, 5855–5860.

(9) Fan, Z.; Ho, J. C.; Takahashi, T.; Yerushalmi, R.; Takei, K.; Ford, A. C.; Chueh, Y.-L.; Javey, A. Toward the Development of Printable Nanowire Electronics and Sensors. *Adv. Mater.* **2009**, *21*, 3730–3743.

(10) Nomura, K.; Ohta, H.; Takagi, A.; Kamiya, T.; Hirano, M.; Hosono, H. Room-Temperature Fabrication of Transparent Flexible Thin-Film Transistors using Amorphous Oxide Semiconductors. *Nature* **2004**, *432*, 488–492.

(11) Takei, K.; Yu, Z.; Zheng, M.; Ota, H.; Takahashi, T.; Javey, A. Highly Sensitive Electronic Whiskers Based on Patterned Carbon Nanotube and Silver Nanoparticle Composite Films. *Proc. Natl. Acad. Sci. U. S. A.* **2014**, *111*, 1703–1707.

(12) Takahashi, T.; Takei, K.; Gillies, A. G.; Fearing, R. S.; Javey, A. Carbon Nanotube Active-Matrix Backplanes for Conformal Electronics and Sensors. *Nano Lett.* **2011**, *11*, 5408–5413.

(13) Sangwan, V. K.; Ortiz, R. P.; Alaboson, J. M. P.; Emery, J. D.; Bedzyk, M. J.; Lauhon, L. J.; Marks, T. J.; Hersam, M. C. Fundamental Performance Limits of Carbon Nanotube Thin-Film Transistors Achieved Using Hybrid Molecular Dielectrics. *ACS Nano* **2012**, *6*, 7480–7488.

(14) Kiriya, D.; Chen, K.; Ota, H.; Lin, Y. J.; Zhao, P. D.; Yu, Z. B.; Ha, T. J.; Javey, A. Design of Surfactant-Substrate Interactions for Roll-to-Roll Assembly of Carbon Nanotubes for Thin-Film Transistors. *J. Am. Chem. Soc.* **2014**, *136*, 11188–11194.

(15) Daeneke, T.; Khoshmanesh, K.; Mahmood, N.; de Castro, I. A.; Esrafilzadeh, D.; Barrow, S. J.; Dickey, M. D.; Kalantar-Zadeh, K. Liquid Metals: Fundamentals and Applications in Chemistry. *Chem. Soc. Rev.* **2018**, *47*, 4073–4111.

(16) Ota, H.; Chen, K.; Lin, Y.; Kiriya, D.; Shiraki, H.; Yu, Z.; Ha, T.-J.; Javey, A. Highly Deformable Liquid-State Heterojunction Sensors. *Nat. Commun.* **2014**, *5*, 5032.

(17) Gao, Y.; Ota, H.; Schaler, E. W.; Chen, K.; Zhao, A.; Gao, W.; Fahad, H. M.; Leng, Y.; Zheng, A.; Xiong, F.; Zhang, C.; Tai, L.-C.; Zhao, P.; Fearing, R. S.; Javey, A. Wearable Microfluidic Diaphragm Pressure Sensor for Health and Tactile Touch Monitoring. *Adv. Mater.* **2017**, *29*, 1701985.

(18) Ota, H.; Emaminejad, S.; Gao, Y.; Zhao, A.; Wu, E.; Challa, S.; Chen, K.; Fahad, H. M.; Jha, A. K.; Kiriya, D.; Gao, W.; Shiraki, H.; Morioka, K.; Ferguson, A. R.; Healy, K. E.; Davis, R. W.; Javey, A. Application of 3D Printing for Smart Objects with Embedded Electronic Sensors and Systems. *Adv. Mater. Technol.* **2016**, *1*, 1600013.

(19) Ota, H.; Chao, M.; Gao, Y.; Wu, E.; Tai, L.-C.; Chen, K.; Matsuoka, Y.; Iwai, K.; Fahad, H. M.; Gao, W.; Nyein, H. Y. Y.; Lin, L.; Javey, A. 3D Printed "Earable" Smart Devices for Real-Time Detection of Core Body Temperature. *ACS Sens.* **2017**, *2*, 990–997.

(20) Park, Y.-L.; Chen, B.-R.; Wood, R. J. Design and Fabrication of Soft Artificial Skin Using Embedded Microchannels and Liquid Conductors. *IEEE Sens. J.* **2012**, *12*, 2711–2718.

(21) Yerushalmi, R.; Jacobson, Z. A.; Ho, J. C.; Fan, Z.; Javey, A. Large Scale, Highly Ordered Assembly of Nanowire Parallel Arrays by Differential Roll Printing. *Appl. Phys. Lett.* **2007**, *91*, 203104.

(22) Fan, Z.; Ho, J. C.; Jacobson, Z. A.; Razavi, H.; Javey, A. Large-Scale, Heterogeneous Integration of Nanowire Arrays for Image Sensor Circuitry. *Proc. Natl. Acad. Sci. U. S. A.* **2008**, *105*, 11066–11070.

(23) Arias, A. C.; MacKenzie, J. D.; McCulloch, I.; Rivnay, J.; Salleo, A. Materials and Applications for Large Area Electronics: Solution-Based Approaches. *Chem. Rev.* **2010**, *110*, 3–24.

(24) Fujisaki, Y.; Koga, H.; Nakajima, Y.; Nakata, M.; Tsuji, H.; Yamamoto, T.; Kurita, T.; Nogi, M.; Shimidzu, N. Transparent Nanopaper-Based Flexible Organic Thin-Film Transistor Array. *Adv. Funct. Mater.* **2014**, *24*, 1657–1663.

(25) Yeom, C.; Chen, K.; Kiriya, D.; Yu, Z.; Cho, G.; Javey, A. Large-Area Compliant Tactile Sensors Using Printed Carbon Nanotube Active-Matrix Backplanes. *Adv. Mater.* **2015**, *27*, 1561–1566.

(26) Sangwan, V.; Behnam, A.; Ballarotto, V.; Fuhrer, M.; Ural, A.; Williams, E. Optimizing Transistor Performance of Percolating Carbon Nanotube Networks. *Appl. Phys. Lett.* **2010**, *97*, 043111.

(27) Takei, K.; Takahashi, T.; Ho, J. C.; Ko, H.; Gillies, A. G.; Leu, P. W.; Fearing, R. S.; Javey, A. Nanowire Active-Matrix Circuitry for Low-Voltage Macroscale Artificial Skin. *Nat. Mater.* **2010**, *9*, 821–826.

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523–533

(28) Wang, C.; Hwang, D.; Yu, Z.; Takei, K.; Park, J.; Chen, T.; Ma, B.; Javey, A. User Interactive Electronic Skin for Instantaneous Pressure Visualization. *Nat. Mater.* **2013**, *12*, 899−904.
(29) Harada, S.; Honda, W.; Arie, T.; Akita, S.; Takei, K. Fully Printed, Highly Sensitive Multifunctional Artificial Electronic Whisker Arrays Integrated with Strain and Temperature Sensors. *ACS Nano* **2014**, *8*, 3921−3927.
(30) Yamamoto, Y.; Harada, S.; Yamamoto, D.; Honda, W.; Arie, T.; Akita, S.; Takei, K. Printed Multifunctional Flexible Device with an Integrated Motion Sensor for Health Care Monitoring. *Sci. Adv.* **2016**, *2*, No. e1601473.
(31) Chortos, A.; Liu, J.; Bao, Z. Pursuing Prosthetic Electronic Skin. *Nat. Mater.* **2016**, *15*, 937−950.
(32) Chen, Z.; Ren, W.; Gao, L.; Liu, B.; Pei, S.; Cheng, H. M. Three-Dimensional Flexible and Conductive Interconnected Graphene Networks Grown by Chemical Vapour Deposition. *Nat. Mater.* **2011**, *10*, 424−428.
(33) Li, W.; Guo, J.; Fan, D. 3D Graphite−Polymer Flexible Strain Sensors with Ultrasensitivity and Durability for Real-Time Human Vital Sign Monitoring and Musical Instrument Education. *Adv. Mater. Technol.* **2017**, *2*, 1700070.
(34) Bariya, M.; Nyein, H. Y. Y.; Javey, A. Wearable Sweat Sensors. *Nat. Electron.* **2018**, *1*, 160−171.
(35) Bandodkar, A. J.; Jeerapan, J.; Wang, J. Wearable Chemical Sensors: Present Challenges and Future Prospects. *ACS Sens.* **2016**, *1*, 464−482.
(36) Yang, Y.; Gao, W. Wearable and Flexible Electronics for Continuous Molecular Monitoring. *Chem. Soc. Rev.* **2019**, DOI: 10.1039/C7CS00730B.
(37) Gao, W.; Emaminejad, S.; Nyein, H. Y. Y.; Challa, S.; Chen, K.; Peck, A.; Fahad, H. M.; Ota, H.; Shiraki, H.; Kiriya, D.; Lien, D.-H.; Brooks, G. A.; Davis, R. W.; Javey, A. Fully Integrated Wearable Sensor Arrays for Multiplexed In Situ Perspiration Analysis. *Nature* **2016**, *529*, 509−514.
(38) Koh, A.; Kang, D.; Xue, Y.; Lee, S.; Pielak, R. M.; Kim, J.; Hwang, T.; Min, S.; Banks, A.; Bastien, P.; Manco, M. C.; Wang, L.; Ammann, K. R.; Jang, K.-I.; Won, P.; Han, S.; Ghaffari, R.; Paik, U.; Slepian, M. J.; Balooch, G.; Huang, Y.; Rogers, J. A. A Soft, Wearable Microfluidic Device for the Capture, Storage, and Colorimetric Sensing of Sweat. *Sci. Transl. Med.* **2016**, *8*, 366ra165.
(39) Lee, H.; Choi, T. K.; Lee, Y. B.; Cho, H. R.; Ghaffari, R.; Wang, L.; Choi, H. J.; Chung, T. D.; Lu, N.; Hyeon, T.; Choi, S. H.; Kim, D. H. A Graphene-Based Electrochemical Device with Thermoresponsive Microneedles for Diabetes Monitoring and Therapy. *Nat. Nanotechnol.* **2016**, *11*, 566−572.
(40) Heikenfeld, J. Non-invasive Analyte Access and Sensing through Eccrine Sweat: Challenges and Outlook circa 2016. *Electroanalysis* **2016**, *28*, 1242−1249.
(41) Emaminejad, S.; Gao, W.; Wu, E.; Davies, Z. A.; Yin Yin Nyein, H.; Challa, S.; Ryan, S. P.; Fahad, H. M.; Chen, K.; Shahpar, Z.; Talebi, S.; Milla, C.; Javey, A.; Davis, R. W. Autonomous Sweat Extraction and Analysis Applied to Cystic Fibrosis and Glucose Monitoring Using a Fully Integrated Wearable Platform. *Proc. Natl. Acad. Sci. U. S. A.* **2017**, *114*, 4625−4630.
(42) Gao, W.; Nyein, H. Y. Y.; Shahpar, Z.; Fahad, H. M.; Chen, K.; Emaminejad, S.; Gao, Y.; Tai, L.-C.; Ota, H.; Wu, E.; Bullock, J.; Zeng, Y.; Lien, D.-H.; Javey, A. Wearable Microsensor Array for Multiplexed Heavy Metal Monitoring of Body Fluids. *ACS Sens.* **2016**, *1*, 866−874.
(43) Nyein, H. Y. Y.; Gao, W.; Shahpar, Z.; Emaminejad, S.; Challa, S.; Chen, K.; Fahad, H. M.; Tai, L.-C.; Ota, H.; Davis, R. W.; Javey, A. A Wearable Electrochemical Platform for Noninvasive Simultaneous Monitoring of Ca^{2+} and pH. *ACS Nano* **2016**, *10*, 7216−7224.
(44) Nakata, S.; Arie, T.; Akita, S.; Takei, K. Wearable, Flexible, and Multifunctional Healthcare Device with an ISFET Chemical Sensor for Simultaneous Sweat pH and Skin Temperature Monitoring. *ACS Sens.* **2017**, *2*, 443−448.
(45) Nyein, H. Y. Y.; Tai, L.-C.; Ngo, Q. P.; Chao, M.; Zhang, G.; Gao, W.; Bariya, M.; Bullock, J.; Kim, H.; Fahad, H. M.; Javey, A. A Wearable Microfluidic Sweat Sensing Patch for Dynamic Sweat Secretion Analysis. *ACS Sens.* **2018**, *3*, 944−952.
(46) Tai, L.-C.; Gao, W.; Chao, M.; Bariya, M.; Ngo, Q. P.; Shahpar, Z.; Nyein, H. Y. Y.; Park, H.; Sun, J.; Jung, Y.; Wu, E.; Fahad, H. M.; Lien, D.-H.; Ota, H.; Cho, G.; Javey, A. Methylxanthine Drug Monitoring with Wearable Sweat Sensors. *Adv. Mater.* **2018**, *30*, 1707442.
(47) Bariya, M.; Shahpar, Z.; Park, H.; Sun, J.; Jung, Y.; Gao, W.; Nyein, H. N. N.; Liaw, T. S.; Tai, L.-C.; Ngo, Q. P.; Chao, M.; Zhao, Y.; Hettick, M.; Cho, G.; Javey, A. Roll-to-Roll Gravure Printed Electrochemical Sensors for Wearable and Medical Devices. *ACS Nano* **2018**, *12*, 6978−6987.
(48) Nassar, J. M.; Cordero, M. D.; Kutbee, A. T.; Karimi, M. A.; Torres Sevilla, G. A.; Hussain, A. M.; Shamim, A.; Hussain, M. M. Paper Skin Multisensory Platform for Simultaneous Environmental Monitoring. *Adv. Mater. Technol.* **2016**, *1*, 1600004.

DOI: 10.1021/acs.accounts.8b00500
Acc. Chem. Res. 2019, 52, 523−533