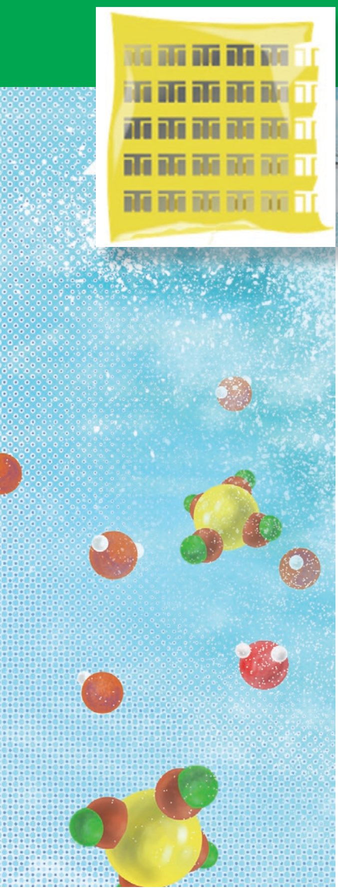
Material strategies for on-demand smart transient electronics

Article *in* MRS Bulletin · February 2020

DOI: 10.1557/mrs.2020.20

Chunyu You
Fudan University

Qinglei Guo
Shandong University



Material strategies for on-demand smart transient electronics

Chunyu You, Haonan Zhao, Qinglei Guo, and Yongfeng Mei

Emerging transient electronics capable of complete physical and chemical disintegration are derived from advanced materials and device design strategies. The area of exploring on-demand smart transient electronics has seen continuous development, allowing for the degradation process to be triggered or controlled through an instantaneous stimulus, thus offering significant potential in data security, undetectable spying, and bioresorbable electronics applications. In this article, we summarize recent progress in the design and strategies of on-demand smart transient electronics and emphasize the basic principles of selecting, processing, and integrating materials. After an introduction to the history and properties of triggered transient electronics, we discuss on-demand smart transient electronics based on their triggering stimuli, strategies for designing thermal, optical, or electrical triggers, and future development trends and challenges.

Introduction

Transient electronics that require materials, devices, or systems to disappear or degrade with little or unmeasurable residues over a period of stable operation[1,2] exhibit great potential in biomedical engineering,[3–12] data security,[13] and disposable electronics.[14,15] The integration of completely or partially vanishable materials, including inorganic or organic semiconductors, metals, and encapsulations/substrates, forms the fundamentals of transient electronics. However, the transience of most transient electronics derives from a spontaneous process such as chemical dissolution or physical disintegration;[16–18] therefore, the operation time is solely dependent on the degradation rate of the integrated materials.

More recently, numerous efforts have been pursued to develop on-demand smart transient electronics so that the transience process can be smartly controlled or triggered by appropriate choices of materials, or particular assemblies of devices, representing a significant step forward for the development of relevant materials science, fabrication technology, and their practical applications. Opportunities for this technology mainly lie in devices/systems with irreplaceable functionalities, such as in biomedical engineering, where functionalities of implanted transient electronics can be degraded or triggered in an on-demand smart manner, or data security, where stored information can be protected or destroyed once it is intercepted.

For this purpose, various types of stimuli such as UV light exposure,[19,20] electrothermal treatments,[21,22] thermal heating,[23–26] and mechanical forces[27] have been demonstrated to trigger on-demand smart transient electronics.

In this article, we will review recent progress in on-demand smart transient electronics. Materials strategies for designing triggering stimuli, including thermal, optical, and electrical triggers are discussed, as well as potential applications. Representative trigger and disintegration mechanisms are examined, and their pros and cons are briefly discussed. Finally, future opportunities for on-demand transient electronics are described.

Thermally triggered transient electronics

To design thermally triggered on-demand smart transient electronics, thermo-sensitive materials, either as encapsulations or substrates (e.g., phase-change and volume-change materials),[17,25,28] are considered. **Figure 1**a shows an example of thermally triggerable on-demand smart transient electronics,[26] with wax-containing methanesulfonic acid drops as triggerable encapsulations. Upon exposure to sufficient thermal heat that reaches the melting point of wax, the encapsulated acid is released, thus inducing the corrosion of the Mg electrodes and failure of the electronic device.

Remotely and precisely thermally triggered transient electronic devices can be achieved.[29,30] Figure 1b shows a wirelessly

Chunyu You, Department of Materials Science, Fudan University, China; cyyou19@fudan.edu.cn
Haonan Zhao, School of Microelectronics, Center of Nanoelectronics, Shandong University, China; zhnlsl@mail.sdu.edu.cn
Qinglei Guo, School of Microelectronics, Center of Nanoelectronics, Shandong University, China; qlguo@sdu.edu.cn
Yongfeng Mei, Department of Materials Science, State Key Laboratory of ASIC and Systems, Fudan University, China; yfm@fudan.edu.cn
doi:10.1557/mrs.2020.20

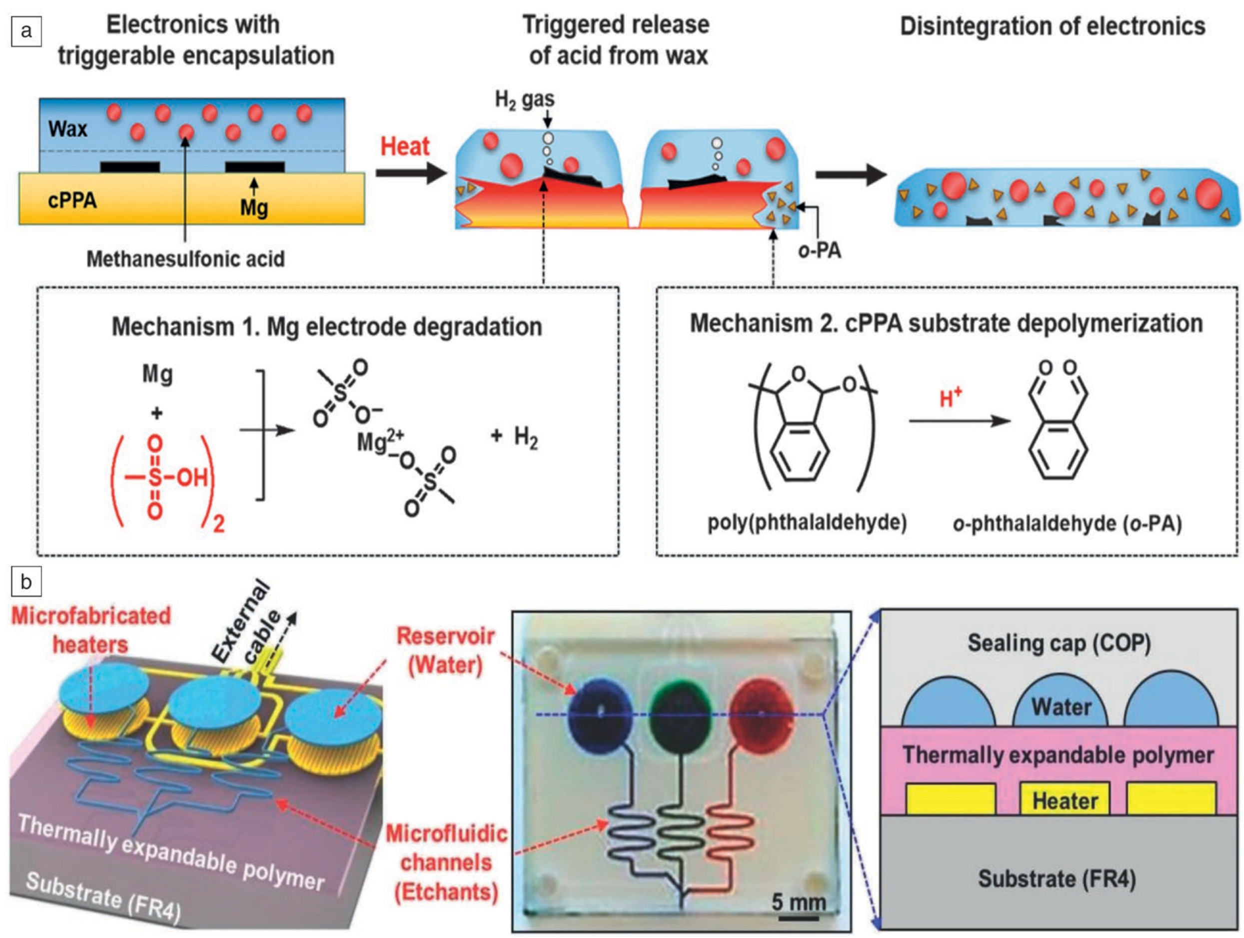


Figure 1. (a) Mechanisms and principles of thermally triggerable transient electronics. Wax containing methanesulfonic acid dispersions is used as the triggerable encapsulation. When the device is heated to 43°C, the wax melts and the encapsulated acid is released, resulting in the erosion of the Mg electrodes and the depolymerization of the cyclic poly(phthalaldehyde) (cPPA) substrate. Reprinted with permission from Reference 26. © 2015 Wiley. (b) Schematic illustration (left), optical image (middle), and side view illustration (right) of a wireless microfluidic system for triggered transience using heat-sensitive pumps. Wirelessly triggered by the thermal heating, chemical etchants will eject through the microfluidic channels into the target electronics, causing the degradation of their functionalities. Reprinted with permission from Reference 29. © 2015 Wiley.

triggerable transient device that contains microheaters, a thermally expandable polymer, reservoirs (for water), sealing caps (made of cyclic olefin polymer), and microfluidic channels on a glass-reinforced epoxy laminate substrate. The wireless control system involving serial communications allows precise control of the microheaters, which induce the ejection of dyed etchants on the functional layer. Within 3 min after the trigger, the transience process was completed. Using a similar scheme, an on-demand, wireless drug delivery system,[23] enabling localized and timed release of drugs, has been demonstrated. In this scenario, all components of the system are made exclusively of bioresorbable materials, including the wireless thermal heaters and the drugs packed and embedded in a thermally triggerable biological lipid membrane. When Joule heat is delivered wirelessly to trigger the phase transition of the lipid membrane, the stored drugs (e.g., doxorubicin) are released, capable of precisely controlling the pharmacological treatment, optimizing current clinical procedures and improving patient compliance.

Thermally triggered transient electronics can also be realized by building the device layer on thermally responsive substrates, such as poly(α-methyl-styrene) (PAMS), which is volatile and decomposable at high temperatures.[25,31] As shown in **Figure 2**, in one study, a PAMS temporary layer was spin-coated on a polyimide/Kapton substrate, and silicon-based electronics were fabricated on top of this layer.[25] When heated to 250°C, the temporary layer starts to decompose, yielding a limited number of volatile products, as shown in Figure 2b. After the critical failure temperature is reached, as presented in Figure 2c, a large quantity of gas gathers below the silicon-based electronics, and the accompanying high pressure leads to the breakdown of the device. With this strategy, Figure 2d–f shows the electrical performances of various types of transient devices, such as silicon-based transistors[25] or phototransistors,[31] that can be triggered to degrade. The studies by Li et al.[25,31] provide great potential in data security, on-chip supervisory circuit

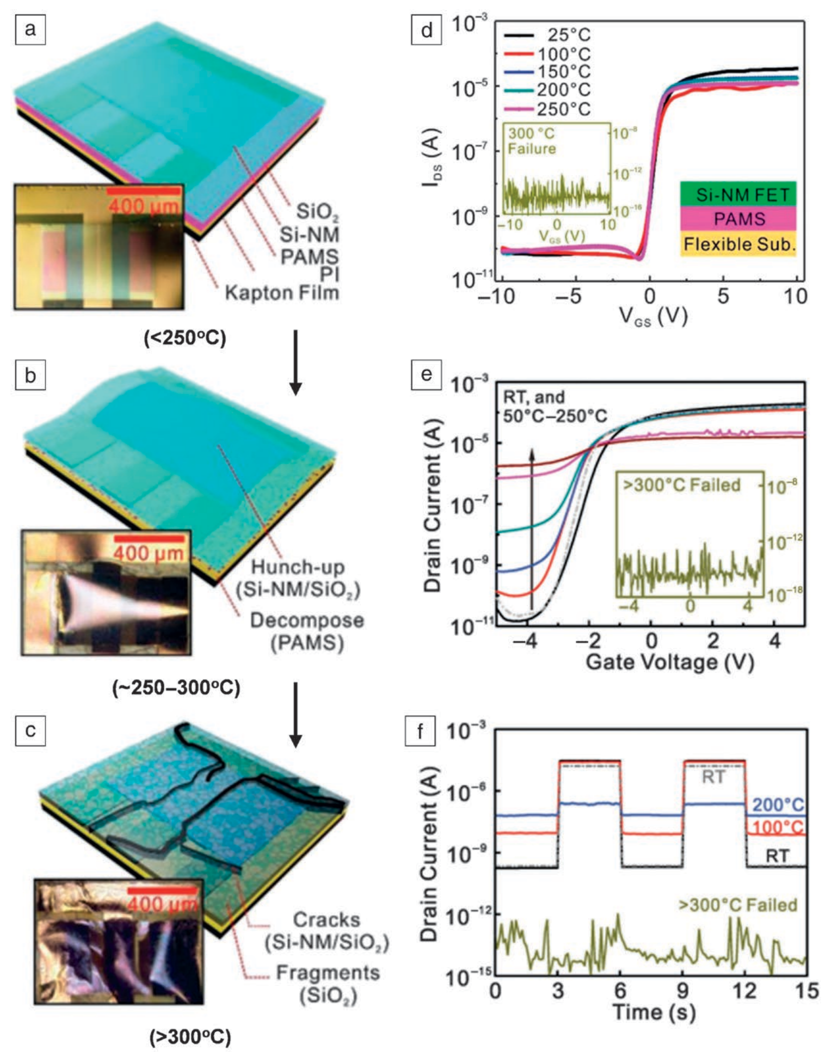


Figure 2. Schematics of the disintegration process of thermally triggered on-demand smart transient electronics. (a) Flexible silicon-based electronics were fabricated on a poly(α-methyl-styrene) (PAMS)/polyimide (PI) substrate. (b) When heated to 250–300°C, the PAMS interlayer starts to decompose causing a high pressure, which hunches up the device layer. (c) When the temperature reaches 300°C, the silicon-based electronics disintegrate via crack formation and delamination. The insets show optical microscope images of corresponding stages. (d) Temperature-dependent transfer characteristics of silicon-based transistors on PAMS. The inset V_{GS}-I_{DS} curve indicates the device is thermally triggered to degrade after heating for 3 min. (a–d) Reprinted with permission from Reference 25. © 2018 Wiley. (e) I_d-V_d (current-voltage) curves collected from a silicon-based phototransistor on PAMS varying with different heating temperatures. The inset shows that the phototransistor is thermally triggered to degrade after heating for 3 min. (f) Real-time (RT) optoelectronic response of the phototransistor illuminated with a pulsed 405-nm laser and various temperatures. When heated over 300°C, the phototransistor completely fails due to the decomposition of PAMS. (e, f) Reprinted with permission from Reference 31. © 2018 Wiley.

safeguards, and sensing devices, although a continuous high-temperature annealing treatment is needed for their strategy. Similar schemes, with rapid transience and low triggered temperatures, are possible through appropriate choice of substrate materials with fast response times and lower response temperatures.[24]

Optically triggered transient electronics

The ability to remotely, noninvasively trigger the transience of on-demand smart transient electronics is useful, especially for sensing/monitoring in severe environments, as recently realized by an optically triggered design.[20] **Figure 3**a shows a typical example of optically triggered transient electronics, consisting of a silicon-based transistor array that is built on the photo-acid generator/cyclic poly(phthalaldehyde) (PAG/cPPA) substrate. Once exposed to ultraviolet light, hydrogen chloride is generated, resulting in the rapid depolymerization of the acid sensitive substrate. Finally, the substrate begins to disintegrate, leading to the destruction of the electronic system.

Optical images of the triggerable transience process of silicon-based transistor arrays fabricated on PAG/cPPA substrates are shown in Figure 3b. After a 230-min irradiation, the substrate was degraded, inducing the destruction of the onboard electronic systems. The transience time can be modified by tuning the substrate material or by optimizing the irradiation conditions. This strategy has been recently expanded to completely dissolve an inert metal (i.e., gold electrodes) by using a light-triggered cyanidation system.[32] Light-responsive metastable polymers (e.g., poly(phthalaldehyde)) that can depolymerize to release a strong acid *in situ* under visible light by the incorporation of photosensitive compounds,[33] may also provide opportunities for optically triggered on-demand smart transient electronics. Further opportunities lie in developing unique materials for realizing a more controllable, environmentally friendly transience process.

Electrically triggered transient electronics

Electrical stimuli that trigger hybrid reactions, such as electric sparks,[22] electrochemical-mechanical distortions,[34] and electrochemical degradations[35] that can induce irreversible failure of devices, offer significant opportunities for data or information security. Data protection through software can be attacked by hackers, or deleted data can be recovered. To eliminate security risks, the most straightforward way for data security is to destroy the data-storage hardware before its interception or decoding, preferably in a way that can be triggered.

Recently, Pandey et al., demonstrated an electrically triggerable transient modular device, which can be electrically triggered to combust.[22] In their scheme, a mixture of preprocessed

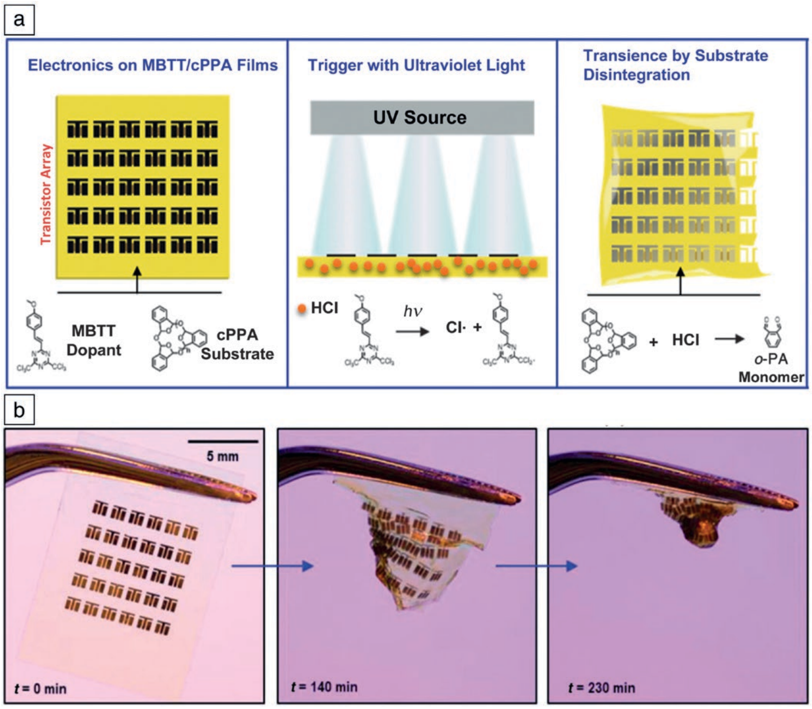


Figure 3. Optically triggered on-demand smart transient electronics. (a) Schematic illustration of the device construction, containing a triggerable 2-(4-methoxystyryl)-4,6-bis(trichloromethyl)-1,3,5-triazine (MBTT)/cyclic poly(phthalaldehyde) (cPPA) substrate, and a transistor array. When exposed to UV light, HCl is generated, leading to rapid depolymerization of the substrate and erosion of the Mg electrodes. (b) Time scale of the degradation process of the proposed optically triggered on-demand smart transient electronics. A 379-nm UV light was used as the triggering source. The freestanding array is completely destroyed after 230-min irradiation. Reprinted with permission from Reference 20. © 2014 Wiley.

CuO particles, Al particles, and a gelling agent in the form of Napalm-B was spin-coated to form a nanothermite film, which acts as the triggerable transient modular. Triggered by an electric spark to generate instantaneous ignition, the on-board silicon-based microelectromechanical chip can be destroyed in approximately 10 s,[22] with the potential to develop any type of triggerable secured microchip.

Recently, Yu et al. designed an on-demand destructive electronic system that can be triggered via electrochemical-mechanical means.[34] **Figure 4**a shows the schematic illustration of the device constructions with on-demand triggered transience, including gold electrolysis electrodes, the corrosive liquid, the controllable releasing module, and functional electronic devices. Applying a DC voltage, the inner gas pressure of a sealed cavity increases through electrolysis of a corrosive solution. Figure 4b shows the diagrams of the key transience steps of the electrically triggered transient electronics. Once the pressure reaches a critical value to induce fracture of the bottom sealed Si_3N_4 layer, the corrosive liquid rushes out to dissolve functional devices. Chen et al. demonstrated an electrochemically triggered transience mechanism for silicon, which allowed complete and controllable destruction of silicon-based electronics.[35] The triggered transience was realized by the lithiation of silicon, which caused fracture of the silicon through significant volume expansion. The proposed strategy may provide an alternative for triggering the transience of silicon-based electronics.

Summary and outlook

On-demand smart transient electronics represent one set of electronic devices or systems that can disappear or lose their functionalities via triggerable or programmable degradation. They offer various opportunities for unusual advanced electronics, mostly significant in biomedical engineering, green consumer electronics, and data security. Materials strategies, device or system construction designs, triggering mechanisms, and fabrication technologies play vital roles in the development of on-demand smart transient electronics. Destruction initiation can be designed within the encapsulations or substrates, which can be triggered electrically, optically, thermally, electromechanically, or electrochemically. Current efforts have demonstrated great potential with this class of emerging electronic devices or systems.

However, the development of on-demand smart transient electronics faces strong challenges, due to complex device configurations, triggering methods that are not ideal, or strong acid-involved chemical reactions. In addition, once the transience stimuli are triggered, materials and components of current on-demand smart transient electronics will be completely degraded or dissolved, leading to a waste of resources. Future research opportunities in this area include (1) exploiting advanced materials and design schemes for friendly stimuli without involving harmful or toxic products (or intermediates) during the whole transience process; (2) designing smarter schemes for triggerable stimuli, aiming for programmable and controllable transience processes; and (3) developing new on-demand smart transient electronics with reversible transience processes or retrievable materials in terms of energy conservation and environment protection.

These on-demand, smart transient electronics promise a bright future for various applications and also lay the foundations for the fast development of several disciplines, including materials science, physics, chemistry, microelectronics, biomedicine, and fabrication technology.

Acknowledgments

C.Y. You and H.N. Zhao contributed equally to this work. Q.L. Guo and Y.F. Mei are the corresponding authors. This work is supported by the Natural Science Foundation of

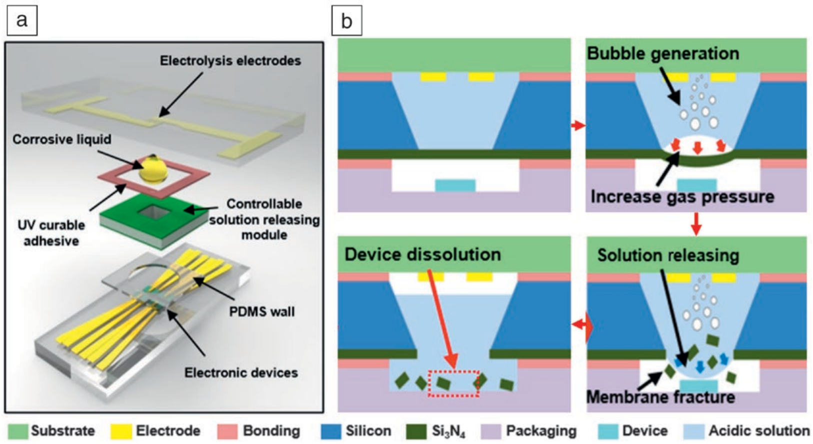


Figure 4. (a) Schematic illustration of the construction of electrically triggered transient electronics, including electrolysis electrodes, corrosive liquid, controllable solution releasing module, and electronic devices. (b) Key materials and steps of the triggered transience. Applied with the electrical triggering, the bubble generation will increase the inner pressure of the sealed cavity, leading to the fracture of the bottom membrane and the release of the solution. Finally, the device will be dissolved to lose its functionalities. Reprinted with permission from Reference 34. © 2014 IOP Publishing. Note: PDMS, poly(dimethylsiloxane).

China (Nos. 61975035 and 51602056), Science and Technology Commission of Shanghai Municipality (17JC1401700), the National Key Technologies R&D Program of China (2015ZX02102–003), the Program of Shanghai Academic Research Leader (19XD1400600), Shandong University Multi-disciplinary Research and Innovation Team of Young Scholars (No. 2020QNQT015), and the Qilu Young Scholar Program of Shandong University.

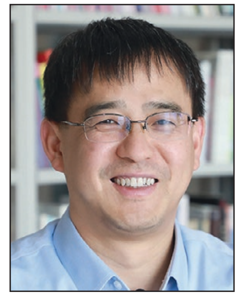
References

1. S.W. Hwang, H. Tao, D.H. Kim, H. Cheng, J.K. Song, E. Rill, M.A. Brenckle, B. Panilaitis, S.M. Won, Y.S. Kim, Y.M. Song, K.J. Yu, A. Ameen, R. Li, Y. Su, M. Yang, D.L. Kaplan, M.R. Zakin, M.J. Slepian, Y. Huang, F.G. Omenetto, J.A. Rogers, *Science* **337**, 1640 (2012).
2. K.K. Fu, Z. Wang, J. Dai, M. Carter, L. Hu, *Chem. Mater.* **28**, 3527 (2016).
3. J.K. Chang, H.P. Chang, Q. Guo, J. Koo, C.I. Wu, J.A. Rogers, *Adv. Mater.* **30**, 1704955 (2018).
4. K.Y. Kwon, J.S. Lee, G.J. Ko, S.H. Sunwoo, S. Lee, Y.J. Jo, C.H. Choi, S.W. Hwang, T.I. Kim, *Small* **14**, 1801332 (2018).
5. L. Yin, A.B. Farimani, K. Min, N. Vishal, J. Lam, Y.K. Lee, N.R. Aluru, J.A. Rogers, *Adv. Mater.* **27**, 1857 (2015).
6. Q. Guo, J. Koo, Z. Xie, R. Avila, X. Yu, X. Ning, H. Zhang, X. Liang, S.B. Kim, Y. Yan, M.R. MacEwan, H.M. Lee, A. Song, Z. Di, Y. Huang, Y. Mei, J.A. Rogers, *Adv. Funct. Mater.* (2019), doi:10.1002/adfm.201905451.
7. T. Lei, M. Guan, J. Liu, H.C. Lin, R. Pfattner, L. Shaw, A.F. McGuire, T.C. Huang, L. Shao, K.T. Cheng, J.B. Tok, Z. Bao, *Proc. Natl. Acad. Sci. U.S.A.* **114**, 5107 (2017).
8. C.M. Boutry, A. Nguyen, Q.O. Lawal, A. Chortos, S. Rondeau-Gagne, Z. Bao, *Adv. Mater.* **27**, 6954 (2015).
9. V.R. Feig, H. Tran, Z. Bao, *ACS Cent. Sci.* **4**, 337 (2018).
10. C.M. Boutry, L. Beker, Y. Kaizawa, C. Vassos, H. Tran, A.C. Hinckley, R. Pfattner, S. Niu, J. Li, J. Claverie, Z. Wang, J. Chang, P.M. Fox, Z. Bao, *Nat. Biomed. Eng.* **3**, 47 (2019).
11. H. Cheng, *J. Mater. Res.* **31**, 2549 (2016).
12. S.K. Kang, R.K. Murphy, S.W. Hwang, S.M. Lee, D.V. Harburg, N.A. Krueger, J. Shin, P. Gamble, H. Cheng, S. Yu, Z. Liu, J.G. McCall, M. Stephen, H. Ying, J. Kim, G. Park, R.C. Webb, C.H. Lee, S. Chung, D.S. Wie, A.D. Gujar, B. Vemulapalli, A.H. Kim, K.M. Lee, J. Cheng, Y. Huang, S.H. Lee, P.V. Braun, W.Z. Ray, J.A. Rogers, *Nature* **530**, 71 (2016).
13. W. Hu, J. Jiang, D. Xie, S. Wang, K. Bi, H. Duan, J. Yang, J. He, *Nanoscale* **10**, 14893 (2018).
14. Y.H. Jung, T.H. Chang, H. Zhang, C. Yao, Q. Zheng, V.W. Yang, H. Mi, M. Kim, S.J. Cho, D.W. Park, H. Jiang, J. Lee, Y. Qiu, W. Zhou, Z. Cai, S. Gong, Z. Ma, *Nat. Commun.* **6**, 7170 (2015).
15. B.H. Lee, D.I. Lee, H. Bae, H. Seong, S.B. Jeon, M.L. Seol, J.W. Han, M. Meyyappan, S.G. Im, Y.K. Choi, *Sci. Rep.* **6**, 38389 (2016).
16. S.-K. Kang, S.-W. Hwang, H. Cheng, S. Yu, B.H. Kim, J.-H. Kim, Y. Huang, J.A. Rogers, *Adv. Funct. Mater.* **24**, 4427 (2014).
17. B.H. Kim, J.-H. Kim, L. Persano, S.-W. Hwang, S. Lee, J. Lee, Y. Yu, Y. Kang, S.M. Won, J. Koo, Y.K. Cho, G. Hur, A. Banks, J.-K. Song, P. Won, Y.M. Song, K.-I. Jang, D. Kang, C.H. Lee, D. Pisignano, J.A. Rogers, *Adv. Funct. Mater.* **27**, 1606008 (2017).
18. L. Yin, H. Cheng, S. Mao, R. Haasch, Y. Liu, X. Xie, S.-W. Hwang, H. Jain, S.-K. Kang, Y. Su, R. Li, Y. Huang, J.A. Rogers, *Adv. Funct. Mater.* **24**, 645 (2014).
19. S. Zhong, X. Ji, L. Song, Y. Zhang, R. Zhao, *ACS Appl. Mater. Interfaces* **10**, 36171 (2018).
20. H.L. Hernandez, S.K. Kang, O.P. Lee, S.W. Hwang, J.A. Kaitz, B. Inci, C.W. Park, S. Chung, N.R. Sottos, J.S. Moore, J.A. Rogers, S.R. White, *Adv. Mater.* **26**, 7637 (2014).
21. J. Yoon, J. Lee, B. Choi, D. Lee, D.H. Kim, D.M. Kim, D.-I. Moon, M. Lim, S. Kim, S.-J. Choi, *Nano Res.* **10**, 87 (2016).
22. S.S. Pandey, N. Banerjee, Y. Xie, C.H. Mastrangelo, *Adv. Mater. Technol.* **3**, 1800044 (2018).
23. C.H. Lee, H. Kim, D.V. Harburg, G. Park, Y. Ma, T. Pan, J.S. Kim, N.Y. Lee, B.H. Kim, K.I. Jang, S.K. Kang, Y. Huang, J. Kim, K.M. Lee, C. Leal, J.A. Rogers, *NPG Asia Mater.* **7**, e227 (2015).
24. Y. Gao, K. Sim, X. Yan, J. Jiang, J. Xie, C. Yu, *Sci. Rep.* **7**, 947 (2017).
25. G. Li, E. Song, G. Huang, Q. Guo, F. Ma, B. Zhou, Y. Mei, *Adv. Funct. Mater.* **28,** 1801448 (2018).
26. C.W. Park, S.K. Kang, H.L. Hernandez, J.A. Kaitz, D.S. Wie, J. Shin, O.P. Lee, N.R. Sottos, J.S. Moore, J.A. Rogers, *Adv. Mater.* **27**, 3783 (2015).
27. C.E. Diesendruck, G.I. Peterson, H.J. Kulik, J.A. Kaitz, B.D. Mar, P.A. May, S.R. White, T.J. Martinez, A.J. Boydston, J.S. Moore, *Nat. Chem.* **6**, 623 (2014).
28. S.M. Won, J. Koo, K.E. Crawford, A.D. Mickle, Y. Xue, S. Min, L.A. McIlvried, Y. Yan, S.B. Kim, S.M. Lee, B.H. Kim, H. Jang, M.R. MacEwan, Y. Huang, R.W. Gereau, J.A. Rogers, *Adv. Funct. Mater.* **28**, 1801819 (2018).
29. C.H. Lee, J.-W. Jeong, Y. Liu, Y. Zhang, Y. Shi, S.-K. Kang, J. Kim, J.S. Kim, N.Y. Lee, B.H. Kim, K.-I. Jang, L. Yin, M.K. Kim, A. Banks, U. Paik, Y. Huang, J.A. Rogers, *Adv. Funct. Mater.* **25**, 1338 (2015).
30. C.H. Lee, S.-K. Kang, G.A. Salvatore, Y. Ma, B.H. Kim, Y. Jiang, J.S. Kim, L. Yan, D.S. Wie, A. Banks, S.J. Oh, X. Feng, Y. Huang, G. Troester, J.A. Rogers, *Adv. Funct. Mater.* **25**, 5100 (2015).
31. G. Li, E. Song, G. Huang, R. Pan, Q. Guo, F. Ma, B. Zhou, Z. Di, Y. Mei, *Small* **14**, 1802985 (2018).
32. W.D. Chen, S.-K. Kang, W.J. Stark, J.A. Rogers, R.N. Grass, *Sens. Actuators B Chem.* **282**, 52 (2019).
33. J. Jiang, O. Phillips, A. Engler, M.H. Vong, P.A. Kohl, *Polym. Adv. Technol.* **30**, 1198 (2019).
34. K. Sim, X. Wang, Y. Li, C. Linghu, Y. Gao, J. Song, C. Yu, *J. Micromech. Microeng.* **27**, 065010 (2017).
35. Y. Chen, H. Wang, Y. Zhang, R. Li, C. Chen, H. Zhang, S. Tang, S. Liu, X. Chen, H. Wu, R. Lv, X. Sheng, P. Zhang, S. Wang, L. Yin, *Nanotechnology* **30**, 394002 (2019). □

Chunyu You is a doctoral candidate in the Department of Materials Science and Engineering at Fudan University, China. He received his BS degree in materials science at Fudan University in 2019. His research interests include flexible electronics and strain engineering. You can be reached by email at cyyou19@fudan.edu.cn.

Haonan Zhao is pursuing her PhD degree in the School of Microelectronics at Shandong University, China. Her current research focuses on flexible and degradable electronic devices. Zhao can be reached by email at zhnlsl@mail.sdu.edu.cn.

Qinglei Guo is a professor in the School of Microelectronics at Shandong University, China. He received his PhD degree from the Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, China, in 2015. He completed postdoctoral research at Fudan University, China, and the University of Illinois at Urbana-Champaign. His research interests focus on developing advanced materials and technologies to construct unusual electronic devices or systems, such as flexible electronics, bioresorbable transient electronics, and soft robotics. He has authored/co-authored more than 50 peer-reviewed papers. Guo can be reached by email at qlguo@sdu.edu.cn.



Yongfeng Mei is a professor in the Department of Materials Science at Fudan University, China. He received his BS and MS degrees in physics from Nanjing University, China, and his PhD degree in materials physics from City University of Hong Kong. He completed postdoctoral research at the Max Planck Institute for Solid State Research, Germany, and then led a research group in the Leibniz Institute for Solid State and Materials Research Dresden, Germany, as a staff scientist. His current research interests focus on the development of inorganic nanomembranes and their properties in optics, optoelectronics, flexible electronics, and micro-/nanoscale robotics. Mei can be reached by email at yfm@fudan.edu.cn.