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Skin-Inspired Electronics: An Emerging Paradigm

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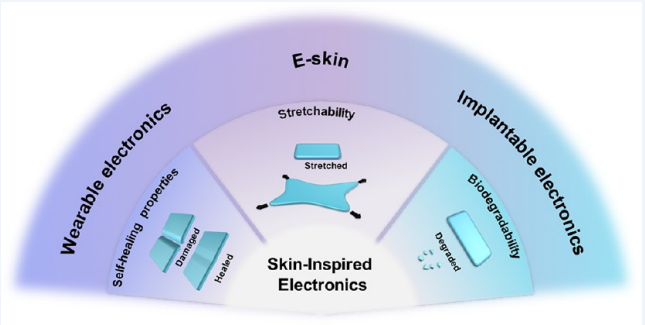
CONSPECTUS: Future electronics will take on more important roles in people's lives. They need to allow more intimate contact with human beings to enable advanced health monitoring, disease detection, medical therapies, and human−machine interfacing. However, current electronics are rigid, nondegradable and cannot self-repair, while the human body is soft, dynamic, stretchable, biodegradable, and self-healing. Therefore, it is critical to develop a new class of electronic materials that incorporate skinlike properties, including stretchability for conformable integration, minimal discomfort and suppressed invasive reactions; self-healing for long-term durability under harsh mechanical conditions; and biodegradability for reducing environmental impact and obviating the need for secondary device removal for medical implants. These demands have fueled the development of a new generation of electronic materials, primarily composed of polymers and polymer composites with both high electrical performance and skinlike properties, and consequently led to a new paradigm of electronics, termed "skin-inspired electronics".



This Account covers recent important advances in skin-inspired electronics, from basic material developments to device components and proof-of-concept demonstrations for integrated bioelectronics applications. To date, stretchability has been the most prominent focus in this field. In contrast to strain-engineering approaches that extrinsically impart stretchability into inorganic electronics, intrinsically stretchable materials provide a direct route to achieve higher mechanical robustness, higher device density, and scalable fabrication. The key is the introduction of strain-dissipation mechanisms into the material design, which has been realized through molecular engineering (e.g., soft molecular segments, dynamic bonds) and physical engineering (e.g., nanoconfinement effect, geometric design). The material design concepts have led to the successful demonstrations of stretchable conductors, semiconductors, and dielectrics without sacrificing their electrical performance. Employing such materials, innovative device design coupled with fabrication method development has enabled stretchable sensors and displays as input/output components and large-scale transistor arrays for circuits and active matrixes. Strategies to incorporate self-healing into electronic materials are the second focus of this Account. To date, dynamic intermolecular interactions have been the most effective approach for imparting self-healing properties onto polymeric electronic materials, which have been utilized to fabricate self-healing sensors and actuators. Moreover, biodegradability has emerged as an important feature in skin-inspired electronics. The incorporation of degradable moieties along the polymer backbone allows for degradable conducting polymers and the use of bioderived materials has led to the demonstration of biodegradable functional devices, such as sensors and transistors. Finally, we highlight examples of skin-inspired electronics for three major applications: prosthetic e-skins, wearable electronics, and implantable electronics.

1. INTRODUCTION

In the foreseeable future, electronics are expected to take more important roles in healthcare, medical therapy, biological studies, and human-machine interfacing.[1] Its realization strongly relies on seamless and intimate integration of electronics with the human body via improved biocompatibility, better conformability, and suppressed invasive reactions.[2−4] Toward this end, skin-inspired electronics has become an emerging research field.

We envision that the long-term development of this field hinges on new generations of electronic materials that concurrently possess skin-like properties and high electrical performance. In this Account, we survey recent important materials and devices developments in skin-inspired electronics, where stretchability, self-healing capability and biodegradability have been independently incorporated. Examples of the integrated skin-inspired electronics are reviewed, which fall into three categories: wearable electronics, prosthetic e-skins, and implantable biomedical electronics.

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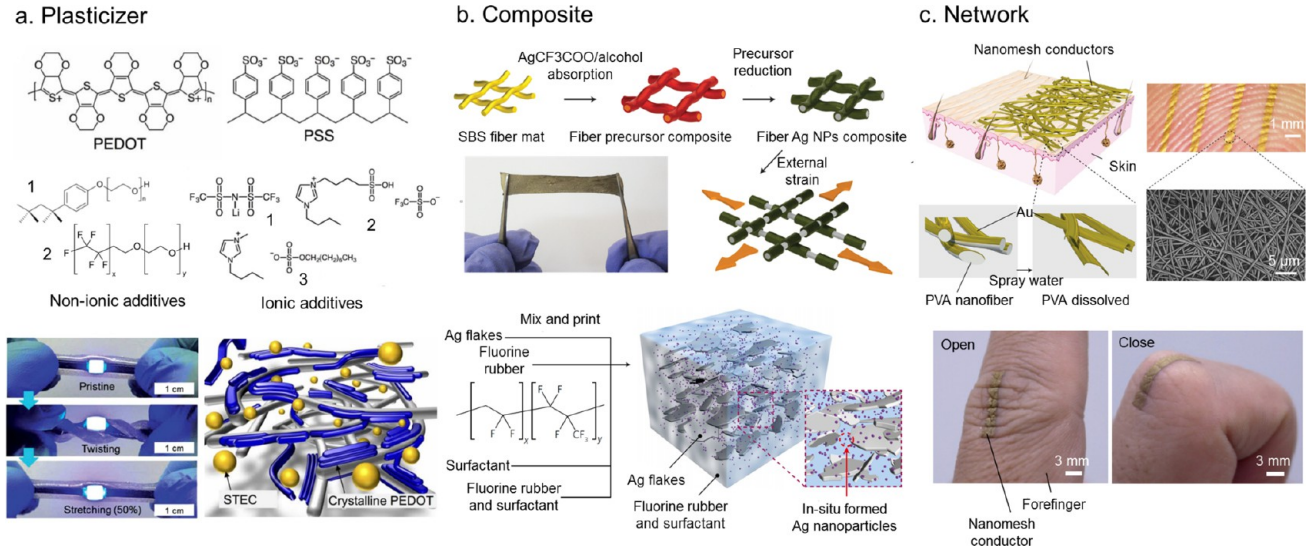

Figure 1. Examples of intrinsically stretchable conductors. (a) Chemical structures of PEDOT:PSS, nonionic and ionic additives. Plasticized PEDOT:PSS as stretchable interconnects (bottom-left) and illustration of the PEDOT:PSS morphology which enables high conductivity and stretchability (bottom-right). (b) Illustrations of a process to form Ag nanoparticle percolation pathways on an elastomer mat (top) and in situ formation of Ag nanoparticles in a fluorinated elastomer (bottom). (c) Nanomesh stretchable conductors on skin. Reproduced with permission from refs 7−11 and 14. Copyright 2012 Wiley, 2016 Wiley, 2017 American Association for the Advancement of Science, 2012 Nature Publishing Group, 2017 Nature Publishing Group, and 2017 Nature Publishing Group, respectively.

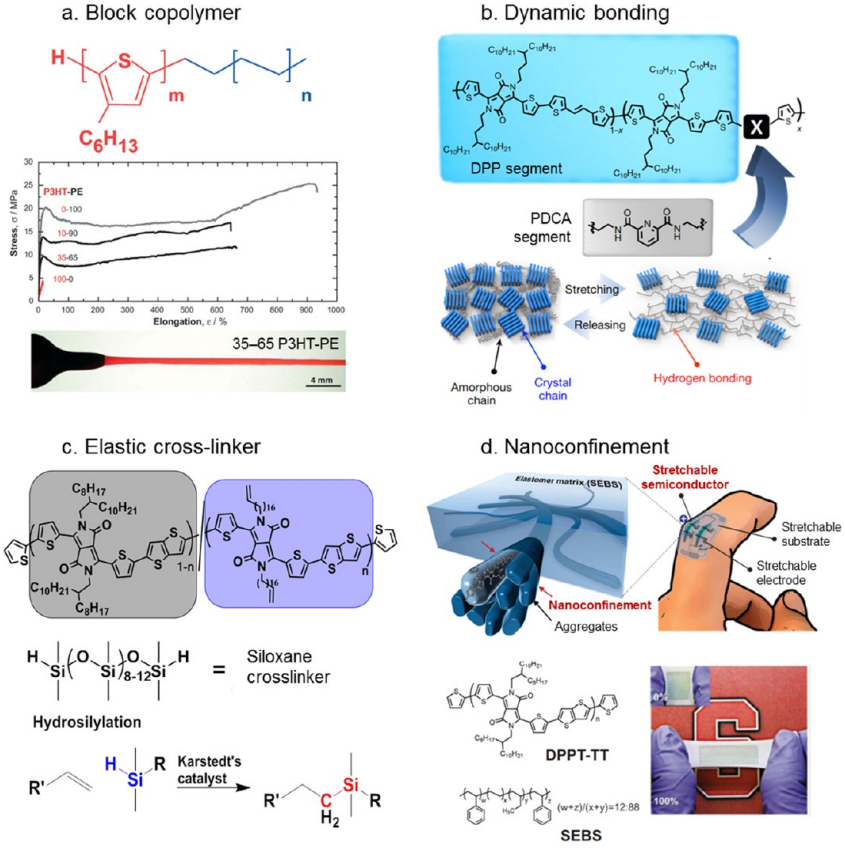

Figure 2. Examples of intrinsically stretchable semiconductors. (a) Chemical structure of poly(P3HT-*b*-PE) (top). Elongation and stress curves as a function of P3HT-PE ratio (middle). Photograph of elongated bulk P3HT-PE (bottom). (b) Chemical structure of DPP and dynamic PDCA segments (top). Illustration of the morphology changes upon stretching (bottom). (c) Chemical structure of cross-linkable DPP-based polymer, elastic cross-linker, and the hydrosilylation reaction. (d) Illustration of nanoconfined DPPT-TT embedded in an elastic matrix (SEBS) (top, bottom-left). Photograph of a stretched semiconducting film (bottom-right). Reproduced with permission from refs 17−19 and 20. Copyright 2007 Wiley, 2016 Nature Publishing Group, 2016 Wiley, and 2017 American Association for the Advancement of Science, respectively.

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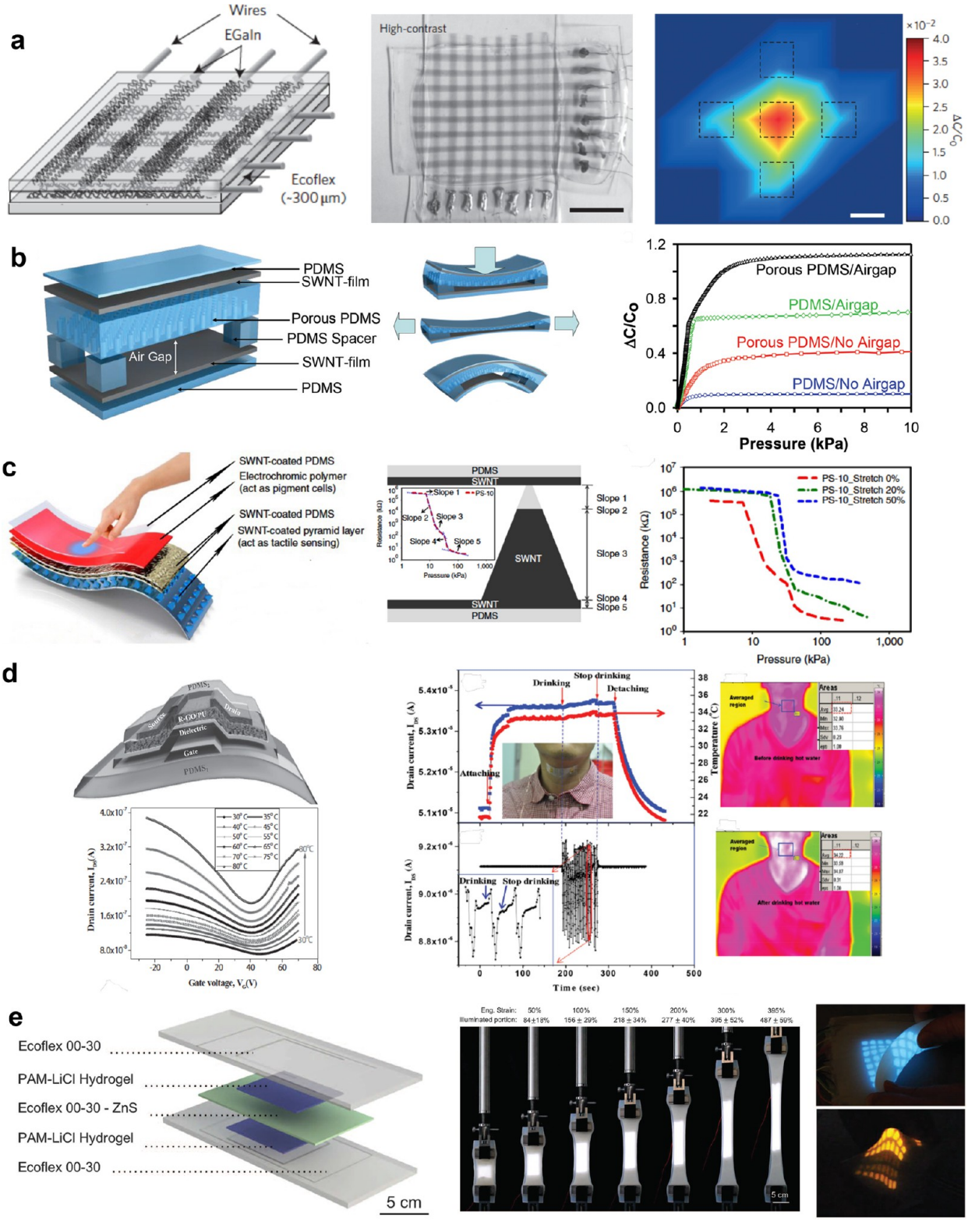

Figure 3. Examples of intrinsically stretchable sensors and displays. (a) Skinlike stretchable strain and pressure sensors composed of CNT conductors and Ecoflex dielectrics, which can be integrated into an array for pressure mapping. (b) Stretchable pressure sensor that can detect and differentiate a variety of mechanical stimuli. (c) Stretchable resistive pressure sensor based on pyramidal-microstructured PDMS, which has been integrated with an electrochromic device. (d) All-elastomeric stretchable and transparent gated temperature sensor. (e) Elastic light-emitting capacitor composed of a ZnS phosphor-doped dielectric elastomer layer sandwiched between transparent hydrogel electrodes. Reproduced with permission from refs 26, 27, 29, 31, and 32. Copyright 2011 Nature Publishing Group, 2014 Wiley, 2015 Nature Publishing Group, 2016 Wiley, and 2016 American Association for the Advancement of Science, respectively.

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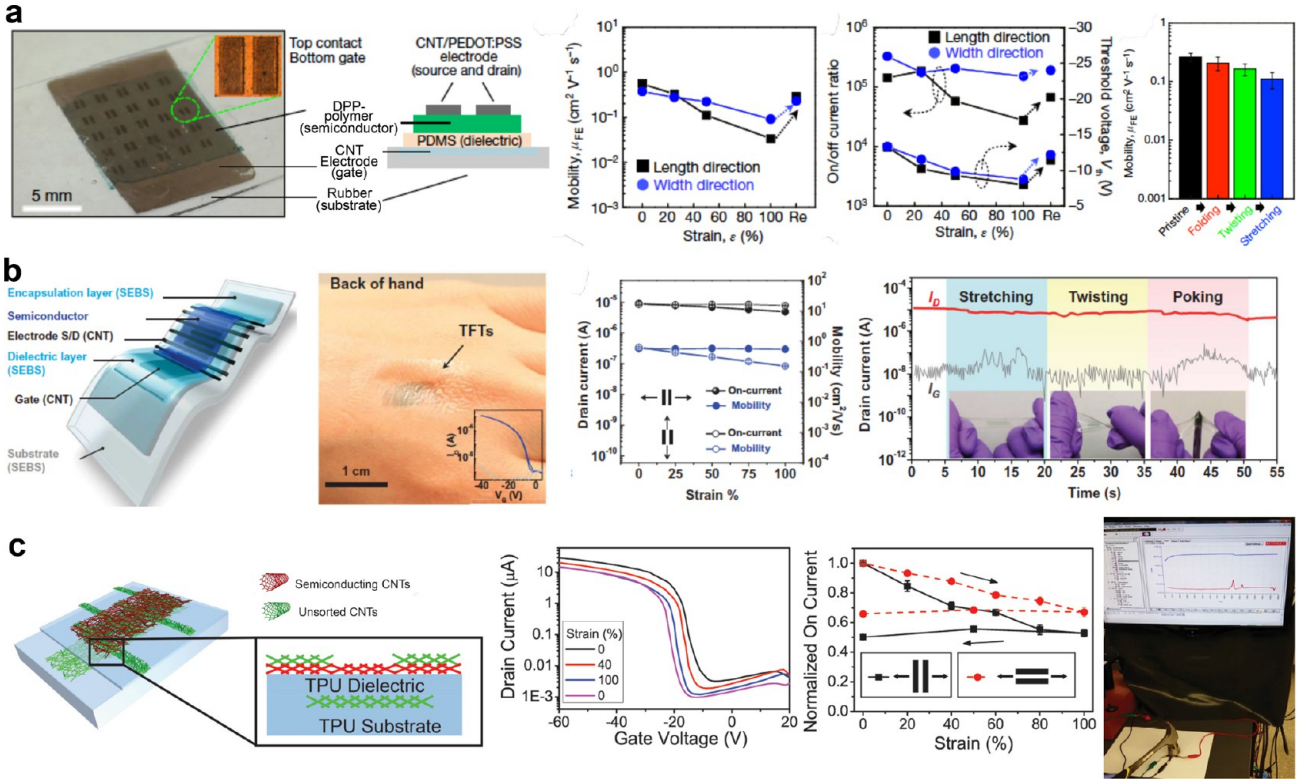

Figure 4. Examples of intrinsically stretchable transistors fabricated as discrete devices. (a) Hydrogen-bonding-incorporated conjugated polymer as the stretchable semiconductor, and PDMS as the stretchable dielectric. (b) CONPHINE-engineered conjugated polymer as the stretchable semiconductor and SEBS as the stretchable dielectric. (c) Polymer-sorted CNT as the stretchable semiconductor and polyurethane as the stretchable dielectric. Reproduced with permission from refs 18, 20, and 39. Copyright 2016 Nature Publishing Group, 2017 American Association for the Advancement of Science, and 2016 Wiley, respectively.

2. STRETCHABILITY

Polymers and its composites may be engineered to possess intrinsic stretchability while retaining its high performance electronic properties, rendering them as prominent candidates for next generation skin-inspired electronic materials. Strain engineering is an effective strategy to introduce extrinsic stretchability to electronic materials that are mechanically rigid.[5,6] However, their limited device density and complex fabrication obstruct their implementation in practical applications.

2.1. Intrinsically Stretchable Materials

In this section, we summarize recent advances in the development of intrinsically stretchable conductors, semiconductors, and dielectrics.

2.1.1. Stretchable Conductors. A ubiquitous highly conductive but lowly stretchable polymer is poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). Its stretchability significantly improves upon addition of nonionic plasticizers (Figure 1a, bottom-left).[7,8] Our group reported ionic additives (Figure 1a, bottom-right) that imparts high stretchability and simultaneously enhances the electrical conductivity (4100 S/cm at 100% strain).[9]

Stretchable conductors can be achieved by preparing composites of stretchable elastomers and metallic fillers (e.g., Ag nanoparticles/flakes, Figure 1b),[10,11] or a network of 1D nanostructured conductive materials.[12,13] Au deposited on sacrificial poly(vinyl alcohol) (PVA) nanofibers yields a Au nanomesh which adheres to skin with high conformability (Figure 1c).[14]

2.1.2. Stretchable Semiconductors. Recent chemical and physical strategies have enabled conventionally rigid polymer semiconductors to be stretchable without compromising its electrical performance.[15] Systematic studies reported that less rigid backbones and side chains that induce less ordered packing were key design parameters.[16] For example, regioregular poly(3-hexylthiophene) (P3HT) was copolymerized with amorphous polyethylene (PE), and resulting copolymers had 600% strain tolerances and mobilities comparable to neat P3HT (Figure 2a).[17]

Noncovalent dynamic cross-linking allows energy dissipation upon strain. Our group introduced 2,6-pyridine dicarboxamide (PDCA) moieties as weak hydrogen bonding sites into a 3,6-di(thiophen-2-yl)-2,5-dihydropyrrolo[3,4-*c*]pyrrole-1,4-dione (DPP) conjugated polymer (Figure 2b).[18] DPP with 10 mol % PDCA can be stretched to 100% strain, and its elastic modulus was reduced by an order of magnitude.

Cross-linking with amorphous oligomers is another strategy to engineer stretchability. A poly(dimethylsiloxane) (PDMS) oligomer was utilized as the elastic cross-linker for a DPP-based semiconducting polymer (Figure 2c).[19] The resulting thin films were highly stretchable.

The nanoconfinement effect is a physical approach to modulate the intrinsic ductility of conjugated polymers by enhancing chain dynamics and suppressing growth of large crystalline domains.[20] Using this concept, our group developed highly stretchable semiconductors with charge carrier mobilities at 100% strain comparable to amorphous Si (Figure 2d).

2.1.3. Stretchable Dielectric. Various elastomers have been employed as stretchable dielectrics.[21] Nonpolar low

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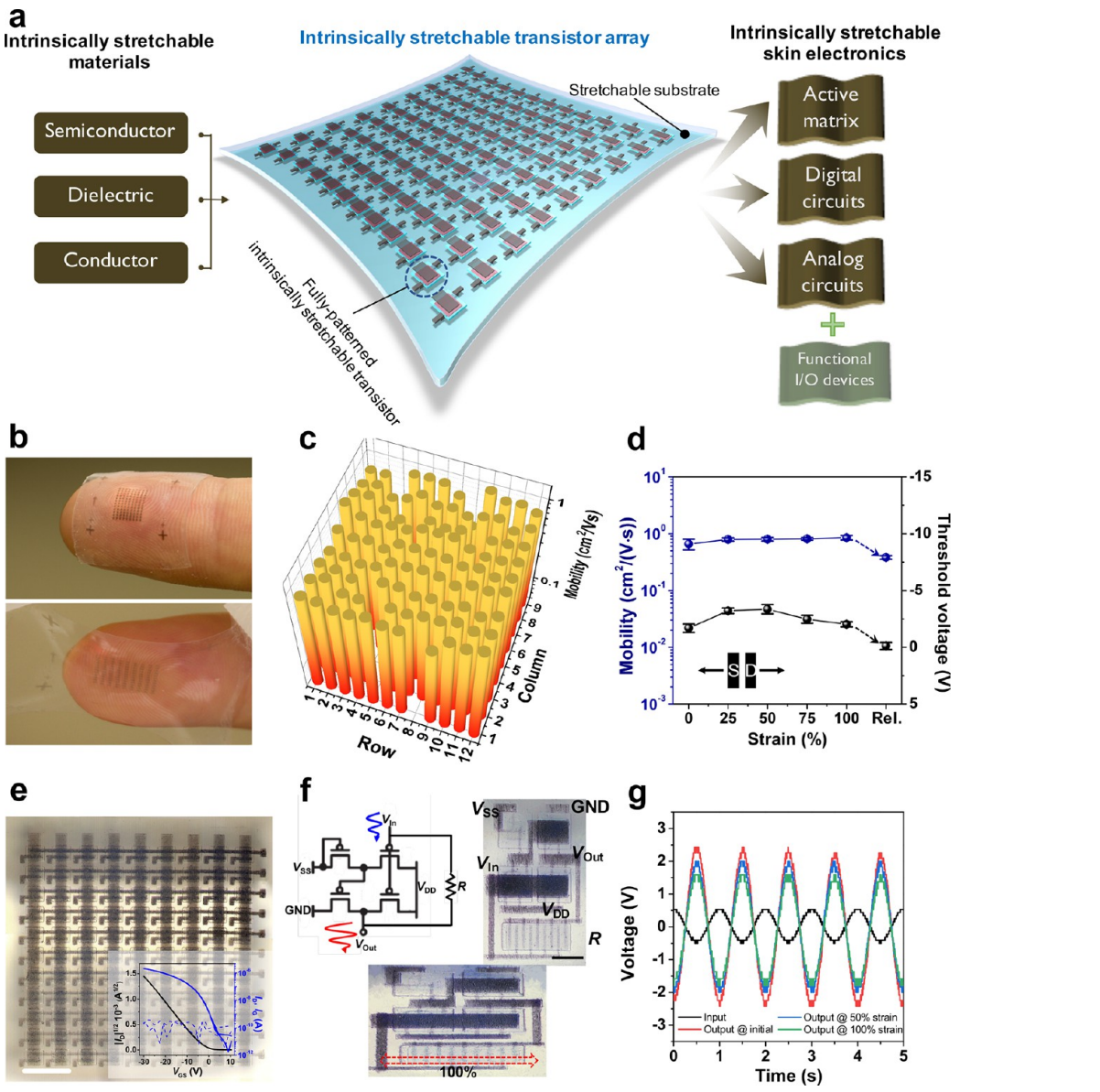

Figure 5. Intrinsically stretchable transistor arrays. (a) Schematic of an intrinsically stretchable transistor array as the core building block for skin-inspired electronics. (b) A 108-stretchable-transistor array on a fingertip (347 transistors/cm^2). (c) Map of charge carrier mobility according to the corresponding transistor location. (d) Mobilities and threshold voltages during a stretching cycle parallel to the channel direction. (e) Stretchable active matrix developed from the intrinsically stretchable transistor array, scale bar: 1 mm. The inset is a typical transfer curve from a transistor in the active matrix. (f) Intrinsically stretchable amplifier. Scale bar: 600 μm. (g) Input sinusoidal signal, and output signals after amplification when the amplifier is at different strains. Reproduced with permission from ref 42. Copyright 2018 Nature Publishing Group.

dielectric constant elastic dielectrics, such as PDMS and poly(styrene-*block*-(ethylene-*co*-butylene)-*block*-styrene) (SEBS), exhibit classical dielectric behaviors. However, low dielectric constants (k < 3) necessitate high operating voltages. More polar and high dielectric constant elastic dielectric materials, such as poly(vinylidene fluoride-*co*-hexafluoropropylene) (PVDF-HFP) and polyurethane (PU), lowers the operating voltage; however, caution must be taken to properly calculate mobility values because unintentional doping by impurities or moisture can result in the double-layer capacitance effect.[22] While composite dielectrics with high-k inorganic nanomaterials and an elastomeric matrix is a potential approach, more in-depth characterizations are needed to fully understand their frequency dependence.[23]

2.2. Intrinsically Stretchable Devices

To transition from intrinsically stretchable materials to devices, innovations in fabrication technologies and device structure designs for minimized strain influence are critical.

2.2.1. Intrinsically Stretchable Sensors and Displays. Compared to transistors, sensor fabrication typically requires less stringent patterning processes and lower device density. In the past few years, intrinsic stretchability has been successfully realized with several major types of sensors.[24]

Mechanical sensors are commonly used for monitoring heart rates, movement and sound. The stretchable strain sensors[25] are mostly based on the geometric piezocapacitive effect[26,27] and piezoresistive effect.[28,29] For example, stretchable strain sensors based on a parallel-plate capacitor structure were built (Figure 3a).[27] Notably, such sensors are also sensitive to other

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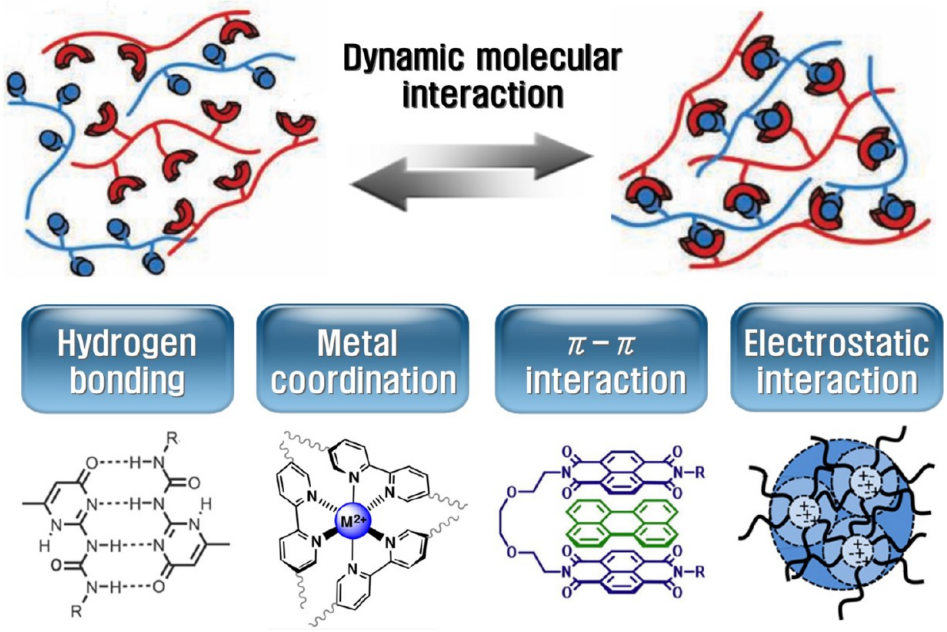

Figure 6. Illustration of dynamic molecular interactions used for the design of self-healing materials.

types of mechanical deformation (e.g., twisting, bending) (Figure 3b).[27,29,30] Besides, stretchable resistive sensors have been constructed by coating carbon nanotubes (CNTs) on the surface of PDMS pyramidal microstructures (Figure 3c).[29] The applied normal pressure induces a decrease in the contact resistance. It is important to further improve the sensing selectivity to pressure over strain.

There have also been efforts toward developing other types of stretchable sensors that are important for wearable and biomedical electronics. By utilizing composite-based temperature sensing mechanisms and transistor operation principles, a stretchable gated temperature sensor was constructed (Figure 3d).[31] In terms of biomarker sensing for health monitoring, stretchable chemical sensors were developed based on floating gate field-effect transistors,[33] electrochemical redox sensing devices,[34] and resistance changes from chemical doping.[35]

On the output end, displays made by light-emitting elements are essential for information visualization. By incorporating elastomers into the active materials, stretchability has been realized with light-emitting capacitors and electrochemical-cells. The recently reported light-emitting capacitor based on ZnS phosphor-doped elastomer demonstrated a high stretchability (480% strain) (Figure 3e).[32] However, the high driving voltage (>1000 V) makes it impractical for on-skin applications. On the other hand, light-emitting electrochemical cells can be operated at relatively low voltages but with relatively low switching speed.[36]

2.2.2. Intrinsically Stretchable Transistors. Compared to sensors and displays, there has been less progress in the development of intrinsically stretchable transistors, due to the more complicated device structure and stringent patterning requirements. Initial reports of stretchable transistors with regioregular P3HT showed low mobilities,[37,38] but recent developments of high performance intrinsically stretchable semiconductors and dielectrics have enabled mobilities approaching 1 $cm^2/(V\ s)$ at 100% strain (Figure 4a).[18,20,39−41] The CONPHINE method enabled intrinsically stretchable transistors with excellent skin-conformability, and an average mobility of 0.55 $cm^2/(V\ s)$ under 100% strain (Figure 4b).[20] Besides, all CNT-based stretchable transistors that remain functional under impacts, punctures, and tears were reported, with polymer-sorted semiconducting CNTs (Figure 4c).[39] Due to the strain-induced morphological change of such CNT network, their performance stability is inferior.

The development of intrinsically stretchable transistor arrays is the key foundation for the realization of functional skin electronics. Recently, our group reported a fabrication process that is applicable to a variety of intrinsically stretchable electronic polymers (Figure 5a).[42] The achieved transistor array (Figure 5b) has an unprecedented device density of 347 cm^{-2}, high yield/uniformity, and high electrical performance with an average mobility of 0.82 $cm^2/(V\ s)$ (Figure 5c). It can be stretched to 100% strain for 1000 cycles with minimal change in the mobility (Figure 5d). Functional electronic elements, such as an intrinsically stretchable active matrix (Figure 5e) as well as analog and digital circuits (Figure 5f, g), were realized.

3. SELF-HEALING

Imparting self-healing capabilities to electronic materials may protect devices against unexpected damages. The material designs have centered on utilizing dynamic intermolecular interactions, such as hydrogen bonding,[43] metal−ligand coordination,[44] $\pi-\pi$ interactions,[45] and electrostatic interactions[46] (Figure 6).[47]

The main approach for achieving self-healing conductors is the preparation of composites, where a self-healing matrix is coupled with conducting filler. Our group developed a self-healing conductor composed of an urea-based polymer with dynamic hydrogen bonding and nanostructured nickel microparticles (μNi) (Figure 7a).[48] The reversible Diels−Alder reaction was exploited as the self-healing mechanism for a composite with Ag nanowires (Figure 7b).[49] The use of liquid metal (E-GaIn) with a stretchable polymer to fabricate reconfigurable wires has also been demonstrated (Figure 7c).[50]

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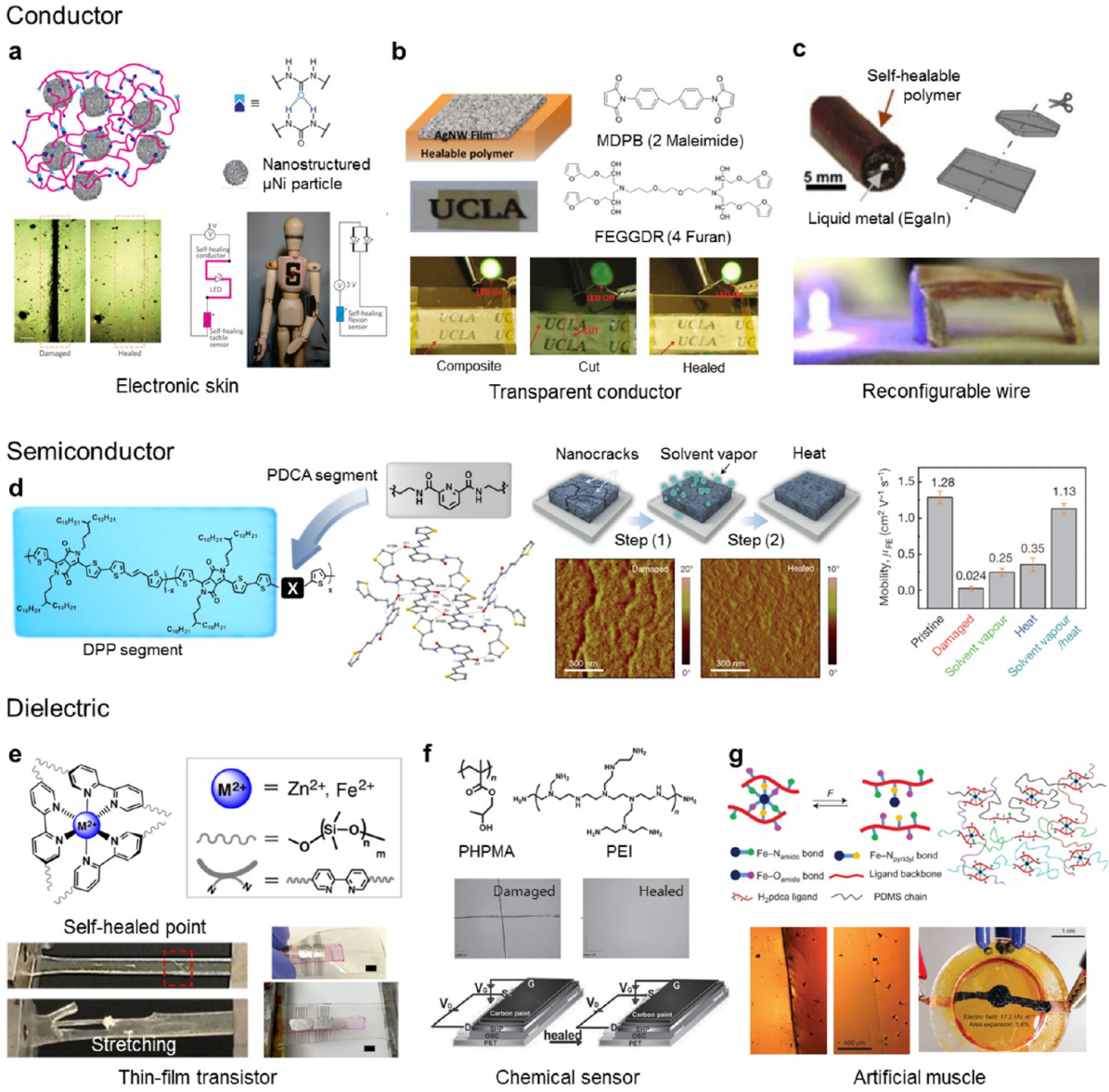

Figure 7. Self-healing electronic materials and devices. (a) Self-healing conductors made from blends of a urea-based self-healing polymer and nanostructured nickel particles. (b) Semitransparent conductor consisting of Diels–Alder-based self-healing polymer and silver nanowires. (c) Reconfigurable wire based on a self-healable elastic polymer and liquid metal (EGaIn). (d) Self-healing semiconducting polymer based on the hydrogen bonding between PDCA. (e) Self-healable elastic dielectric by metal ligand coordination, which has been used for fully stretchable transistor. (f) Organic thin-film transistor (OTFT)-based chemical sensor based on PHPMA and PEI polymers. (g) Self-healable artificial muscle from PDCA metal coordination complex. Reproduced with permission from refs 48–50, 18, 44, 52, and 51. Copyright 2012 Nature Publishing Group, 2013 Wiley, 2013 Wiley, 2016 Nature Publishing Group, 2016 American Chemical Society, 2015 Wiley, and 2016 Nature Publishing Group.

Healable semiconductors were achieved by incorporating weak hydrogen bonding as noncovalent dynamic cross-linkers (Figure 7d).[18] Solvent vapor and heat treatments can activate polymer chains for healing nanocracks in thin films, nearly recovering its FET mobility.

A common motif for self-healing dielectrics is cross-linking via metal–ligand coordination (Figure 7e, g).[44,51] Fe^{+} was reported as an effective metal for dynamic coordination for stretchable organic thin-film transistors (OTFTs, Figure 7e) and artificial muscle (Figure 7g). Blends of complementary poly(2-hydroxypropyl methacrylate) (PHPMA) and poly(ethylenimine) (PEI) provide a sufficient hydrogen bonding network for self-healing, and it can be used as a chemical sensor to detect NH_3 (Figure 7f).[52]

Currently, autonomously self-healing of thin-films (<1 μm) at room temperature without post-treatment are still challenging for most electronic devices with submicrometer layers.

4. BIODEGRADABILITY

One of the purposes for developing skin-inspired electronics is their potential use as implantable biomedical devices for diagnosis, treatment and monitoring. Side effects from permanent implants and the extraction surgery remain as major obstacles. Biodegradable electronics that can function over prescribed time frames then physically degrade into nonharmful constituents would alleviate the aforementioned concerns. Also, there is a need to relieve the environmental threat from the rapid growth of electronic waste.

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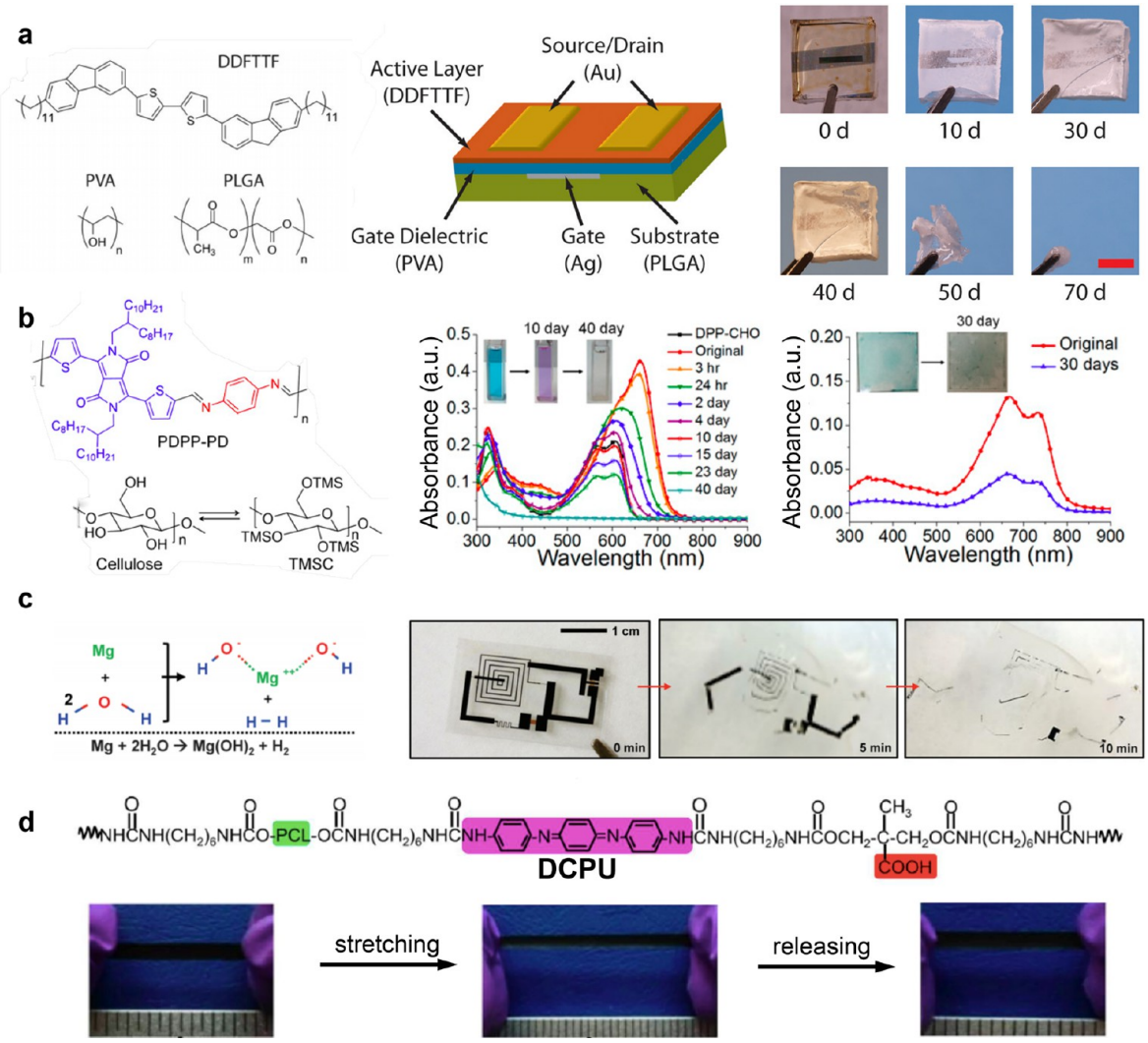

Figure 8. Examples of degradable materials development. (a) Biodegradable PLGA and PVA were utilized as the substrate and dielectric layer in a thin film transistor. (b) Synthetic degradable conjugated polymer using reversible imine chemistry served as a semiconducting layer. (c, d) Degradable conducting materials based on inorganic Mg and organic conductive polyurethane elastomer. Reproduced with permission from ref 56, 54, 53, and 61. Copyright 2010 Wiley, 2017 National Academy of Sciences, 2012 American Association for the Advancement of Science, and 2016 Nature Publishing Group.

Both materials found in nature (e.g., silk,[53] cellulose,[54] and gelatin[55]) and synthetic polymers (e.g., poly(lactic-*co*-glycolic acid) (PLGA);[56] poly(1,8-octanediol-*co*-citrate)[57]) are utilized as the biodegradable insulating materials in electronic devices. For example, our group fabricated an OTFT on a PLGA substrate with a near-total device resorption time of 70 days (Figure 8a).[56] Compared to the wide exploration of biodegradable insulators, research efforts in biodegradable semiconductors, especially polymer-based, remain sparse. Recently, our group synthesized the first completely decomposable conjugated polymer using reversible imine chemistry (Figure 8b).[54] These ultrathin flexible electronics completely degraded within 30 days.[54] Although physiologically friendly metals, such as magnesium (Figure 8c)[53] and iron,[54,58] are the favored candidates as electrodes due to their high conductivity, polymer-based biodegradable conducting materials is an exciting prospect because of their mechanical softness and potential of possessing both electronic and ionic conduction. Currently, there are two main types of organic biodegradable conducting materials. One is the conductive composites that contain biodegradable polymers with conductive polymers[59] or inorganic nanomaterials.[60] The other one is block copolymers composed of conductive and biodegradable moieties. A recent example features a PU-based polymer comprised of biodegradable polycaprolactone diol and conductive aniline trimers (Figure 8d).[61] Although exhibiting high elasticity, the conductivity of these materials remains low and does not meet the demands for electronics, especially as interconnects.

Various biodegradable electronics have been developed. A highly sensitive pressure sensor array was reported by our group for cardiovascular monitoring (Figure 9a).[58] We employed the disintegrable semiconducting polymers to fabricate biodegradable flexible circuits (Figure 9b).[54] The Rogers' group has fabricated a series of biodegradable devices with different functionalities, such as ECG and EMG sensors (Figure 9c).[53,57,62] Physical and synthetic strategies for developing biodegradable electronic components with high electrical performance still need to be explored, particularly with the incorporation of other skinlike properties.

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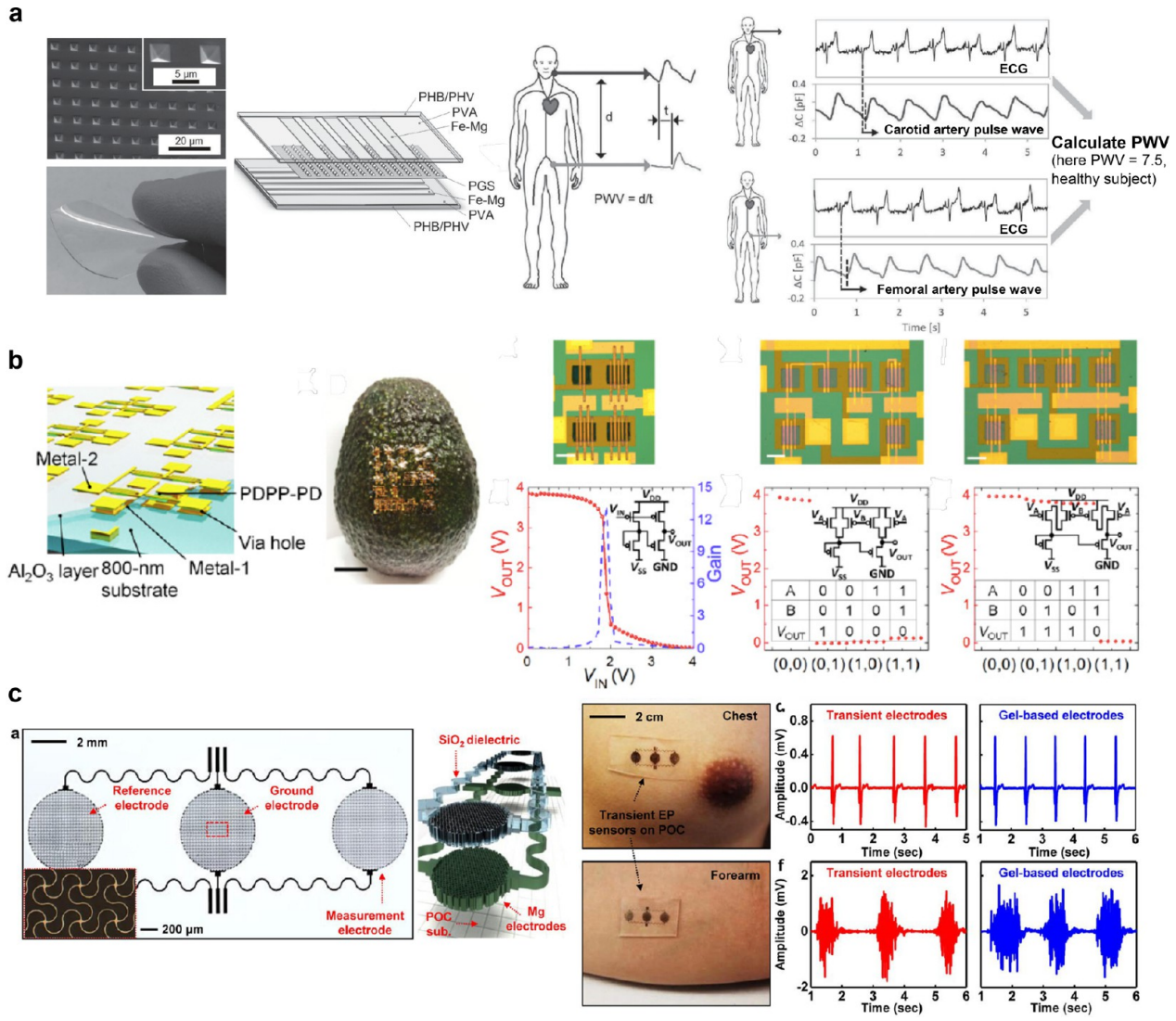

Figure 9. Examples of functional electronic devices utilizing degradable materials. (a) Sensitive and biodegradable pressure sensor array fabricated from microstructured biodegradable elastic poly(glycerol sebacate) (PGS) films for cardiovascular monitoring. (b) Pseudo-complementary metal–oxide–semiconductor flexible circuits based on disintegrable semiconducting polymers show good electrical behavior as an inverter, NOR and NAND gate. (c) Capacitive biodegradable, stretchable electrophysiological sensors for measurement of ECG and EMG signals. Reproduced with permission from refs 58, 54, and 57. Copyright 2015 Wiley, 2017 National Academy of Sciences, and 2015 American Chemical Society.

5. INTEGRATED BIOELECTRONIC APPLICATIONS OF SKIN ELECTRONICS

There have been preliminary efforts of implementing the three desired properties (i.e., stretchability, self-healing, and biodegradability) into the major application areas for skin-inspired electronics: prosthetic e-skins, implantable electronics, and wearable electronics (Figure 10a). To date, the demonstrated examples have incorporated at most two of these properties, which often resulted in compromised electronic functionalities.

One of the main drivers for the development of skin-inspired electronics is to mimic the functionalities of skin for the applications in advanced prosthetics and robotics. Our group demonstrated a flexible, artificial mechanoreceptor system that emulated the response of slow-adapting mechanoreceptors by encoding static pressure stimuli into digital frequency signals controlled by an applied pressure (Figure 10b).[63]

Strain-engineering approaches have been employed to achieve stretchability for implantable bioelectronics interfaces.[64,65] For example, through the controlled formation of microcrack morphology in Au films, the Lacour group developed soft neural implants for neuroprosthetic applications (Figure 10c).[65] As for the biodegradability, Rogers et al. reported multifunctional rigid silicon sensors for the brain, which naturally resorbed via hydrolysis and/or metabolic action (Figure 10d).[62]

Wearable electronics are designed to operate on the human body for health monitoring or perception enhancement. The strain-engineering approach has enabled several multifunctional stretchable wearable systems by bounding Si-chips or other rigid components onto elastomer substrates;[66−68] however, it suffers from limited mechanical robustness and skin conformability. Recently, the first prototype for intrinsically stretchable and fully functional wearable electronic systems has been demonstrated (Figure 10e), which included a sensor unit for signal collection and an amplifier circuit for signal processing.[42]

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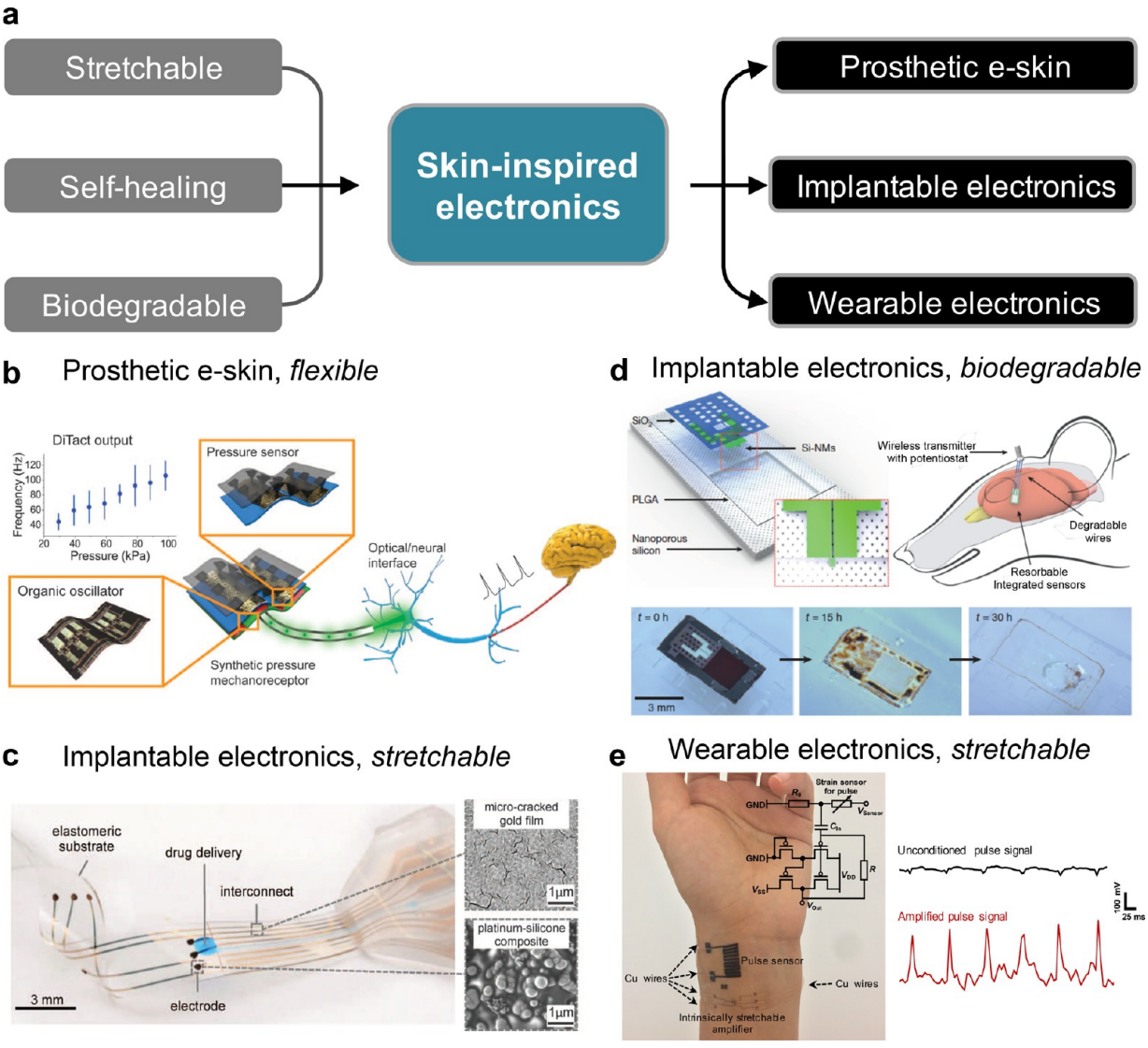

Figure 10. Applications for skin-inspired electronics. (a) Major application areas for skin-inspired electronics. (b) Prosthetic e-skin demonstrated based on a skin-inspired flexible organic digital mechanoreceptor. (c) Stretchable neural implants demonstrated for multiple neuroprosthetic applications. (d) Implantable, multifunctional, resorbable silicon sensors for the brain. (e) Prototypical demonstration for intrinsically stretchable wearable electronics, which contains both a resistive pulse sensor and a signal-processing unit. Reproduced with permission from refs 63, 65, 62, and 42. Copyright 2015 American Association for the Advancement of Science, 2015 American Association for the Advancement of Science, 2016 Nature Publishing Group, and 2018 Nature Publishing Group.

6. SUMMARY AND OUTLOOK

In this Account, we have reviewed recent advances in skin-inspired electronics, highlighting stretchability, self-healing properties, and biodegradability. There have been a number of new design concepts validating the feasibility of electronic materials and devices that can incorporate these properties without compromising their electrical performance. A better fundamental understanding of the interplay between molecular design, microstructures, and their mechanical and electronic properties is critical for guiding further development of next generation materials. Improved processing and patterning methods are needed to incorporate high-performance materials as they are being developed. Characterization of devices under conditions that they are intended for future applications will be important for providing feedback on limitations and issues of current materials. As a whole, the need for skin-inspired electronics for wearable electronics and implantable electronics provides motivation for new materials development, which may in turn enable other unforeseen applications.

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Notes

The authors declare no competing financial interest.

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Institute of Technology under the supervision of Prof. Zhong Lin Wang, and his Bachelor's degree from Tsinghua University. His research interests include stretchable polymer electronics, e-skins, and mechanical energy harvesting.

Jin Young Oh received his Ph.D. from Yonsei University. After spending 3 years as a postdoctoral fellow at Stanford, He joined Kyung Hee University as an assistant professor in 2018. His current research focuses on stretchable and self-healable electronics.

Jie Xu is a postdoctoral fellow at Stanford. She received her Ph.D. degree in Polymer Physics and Chemistry from Nanjing University under the supervision of Prof. Gi Xue, and her B.S. from Nanjing University. Her research focuses on nanoconfinement effect, polymer assembly process, and processing methodologies for controlling molecular packing.

Helen Tran is a postdoctoral researcher at Stanford. She received her B.S. from UC Berkeley, and completed her Ph.D. at Columbia University under the supervision of Prof. Luis Campos. Her current research focuses on high-performance, stretchable electronics that are biodegradable.

Zhenan Bao received her Ph.D. from University of Chicago. After spending 8 years in Bell Laboratories as a Distinguished Member of Technical Staff, she joined Stanford as an Associate Professor in 2004. She is a member of the National Academy of Engineering. Selected recent awards include ACS Polymer Science Award in 2017, and L'Oréal-UNESCO Women in Science Prize in 2017.

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