Matter

Review

Advances in Physicochemically Stimuli-Responsive Materials for On-Demand Transient Electronic Systems

Geumbee Lee,^{1,2,3,7} Yeon Sik Choi,^{1,2,3,7} Hong-Joon Yoon,^{1,2,3,4,7} and John A. Rogers^{1,2,3,5,6,*}

SUMMARY

Transient electronics represents a class of technology defined by components that physically or chemically disintegrate, dissolve, or otherwise disappear in a controlled manner for application opportunities that lie outside of those that can be addressed with conventional, permanent devices. Materials and system designs that allow for initiation of the transient processes upon well-defined trigger events are of particular interest for uses in areas such as hardware-level data security, unrecoverable proprietary electronics, and certain classes of temporary biomedical implants. Progress relies on the development of advanced materials for this purpose and a detailed understanding of the mechanisms by which they respond to various physicochemical stimuli. This review summarizes a diverse range of materials recently explored in this context, with responsiveness to changes in temperature, exposure to water, illumination with light, and delivery of electrical current. Subsequent sections present demonstrations of these materials as the basis for triggered transient devices with active operation. Strategies that exploit a cascade or a combination of triggering events represent important additional trends in this field of technology, laying the groundwork for a broad range of electronic devices with precisely controlled lifetimes.

INTRODUCTION

Research in electronics has historically emphasized high-performance, reliable operation, with invariant characteristics over long periods of time, as an essential goal of engineering design and materials development (Figure 1A). An emerging and complementary area of interest is in systems that consider the opposite approach, where the devices themselves have a finite physical lifetime aligned with application requirements. The ultimate fate of such technologies, referred to as transient electronics, is "disappearance without a trace." Electronics with transient characteristics first appeared in an example of silicon transistors on water-soluble substrates (i.e., silk) in 2009 in a report by Kim et al.¹ Studies thereafter explored the dissolution kinetics of wide-ranging classes of conductors, semiconductors, and insulators that undergo hydrolysis under various parameters (e.g., surface morphology, chemical composition/ionic concentration, pH and temperature of the solution, and methods/conditions for depositing the thin films). These fundamental efforts in materials science led to advanced work at the device and systems levels. Typically, such systems cease to function due to mechanical disruption and/or chemical degradation in a timed fashion with some combination of internal and external physicochemical stimuli.² Technologies of this type can be divided into two main categories passive and active—as defined by the nature of these transient processes (Figure 1B). Passive refers to situations where transience begins immediately upon device

Progress and Potential

CellPress

Transient electronic systems represent a unique class of technology defined by an ability to fully or partly dissolve, resorb, or otherwise physically disappear with controlled rates or at triggered times. Recent research establishes the foundations for a wide range of vanishing materials and devices of this type, with potential applications in fields that span temporary medical implants, environmentally degradable sensors, physically secure data storage systems, zero-waste consumer and industrial electronics, nontraceable proprietary platforms, and so on. Many of these examples include stimuliresponsive operation where welldefined triggering events initiate the transient response, as opposed to those that rely on passive, gradual processes that begin immediately at the time of deployment. These stimuli include controlled exposures to solvents, heat, light, electromechanical impulses, and others. The materials that support these behaviors represent areas of interest for further research in this dynamic and evolving field. This review summarizes recent progress in materials for stimuliresponsive transient electronics and the mechanisms that underpin their behaviors in the context of triggered changes in properties and performance.









Figure 1. Conceptual Diagrams that Highlight Operation in Conventional and Active and Passive Transient Electronic Systems

(A) Conventional permanent electronic system. Well-engineered devices offer invariant performance characteristics that extend over long periods of time.

(B) Transient electronic systems in passive and active forms. The gradual degradation of device performance occurs as a result of mechanical disruption and/or chemical reaction, depending on the constituent materials and the device designs. Passive systems correspond to those with transient processes that begin with exposure to the surrounding environment, immediately upon device deployment. Careful designs lead to stable performance during a period when the transience involves only the substrate and/or encapsulation materials, followed by continuous degradation thereafter (left). Active systems are those for which the degradation begins at a specific time determined by a trigger event (right).

deployment and/or operation, as initiated automatically upon interaction with the surrounding environment. In well-designed systems, the initial stages of this passive transience process affect only the encapsulation structures, such that the performance remains constant during this period. By contrast, active systems operate without change until exposed to specific stimuli that serve as triggers to initiate transient processes. Engineering designs often involve two types of materials: one that responds to an external stimulus and determines the onset of the device failure and the other that supports the essential functions. Thus, design considerations include not only the material properties but also the interaction between stimuli-responsive materials, triggering events, and neighboring environments to precisely define the device lifetime on demand.

Although active operation represents a key advantage in nearly all envisioned applications of transient electronics, many use cases can be addressed adequately with passive designs. For example, one of the most interesting and compelling areas of application is in temporary biomedical implants, where stable operation must simply exceed the time frame for a relevant biological process (i.e., wounds generally heal in 4–6 weeks).^{2–7} After this period, the devices, sometimes referred to as bioresorbable or bioabsorbable, can disappear naturally over some subsequent period to eliminate unnecessary loads on the body and risks to the patient, without the need for surgical extraction. Recent publications describe a variety of such devices, including those for sensing pressure in the intracranial space,³ mapping electrical activity from the cerebral cortex,⁴ and electrically stimulating peripheral nerves to accelerate neuroregeneration.⁶ The time intervals between the loss of functionality and the complete disappearance of these devices can, however, be quite long and, in this sense, non-ideal from the standpoint of patient health.

Nevertheless, in many such cases, complete transience can occur over these long timescales, without need for precise control. For example, environmentally degradable electronics can often behave in this fashion, without critical need for active transience. The opportunity here is in addressing challenges associated with the rapidly growing accumulation of electronic waste associated with the expansion of the electronics industry and the reduction in product cycle life. Discarded devices and

¹Center for Bio-Integrated Electronics, Northwestern University, Evanston, IL 60208, USA

²Querrey Simpson Institute for Biotechnology, Northwestern University, Evanston, IL 60208, USA

³Department of Materials Science Engineering, Northwestern University, Evanston, IL 60208, USA

⁴School of Advanced Materials Science and Engineering, Sungkyunkwan University (SKKU), Suwon 16419, Republic of Korea

⁵Department of Biomedical Engineering, Chemistry, Mechanical Engineering, Electrical Engineering, Computer Science and Neurological Surgery, Northwestern University, Evanston, IL 60208, USA

⁶Department of Neurological Surgery, Feinberg School of Medicine, Northwestern University, Chicago, IL 60611, USA

⁷These authors contributed equally

*Correspondence: jrogers@northwestern.edu https://doi.org/10.1016/j.matt.2020.08.021



components largely accumulate in lower- and middle-income countries through exporting of this waste from wealthy countries.^{8,9} Incineration is the primary means for eliminating this waste, but this process is energy intensive and it can generate gases that are harmful to the environment, with negative consequences for surrounding populations and ecosystems.^{10,11} Transient electronic systems that degrade naturally into environmentally benign end products represent a potentially important means to address these challenges, where passive operation can suffice in most scenarios.

In these instances, active transience is an option, but in others it is essential. One example is in strategies for data security that exploit transient memory modules. Here, the concept is that a trigger event can lead to the elimination of stored sensitive information at the level of the hardware itself. Another area is in sensitive electronics in military or proprietary industrial systems, where risks of recovery by an adversary can be eliminated by using a remotely triggered transience mechanism.^{12,13} In these and other scenarios, high-energy approaches based on explosives or fuses or other obvious options may be relevant, but physical hazards, safety considerations, and lack of precise control represent key drawbacks.

A frontier area for research in materials science is to create alternatives to these rudimentary active transient electronic devices through the development of comparatively low-energy, stimuli-responsive materials and devices. Progress will not only address applications that demand active operation but it will potentially enhance others. For example, materials that dissolve in biofluids within minutes or hours are not appropriate for implantable systems that must operate for several days. Materials that react slowly, or not at all, in such environments fail to capture many of the benefits of bioresorbability. Devices or residues of devices that persist for excessively long periods of time increase the potential for adverse tissue reactions and other negative health consequences. In all cases, a fundamental understanding of the physicochemical characteristics of the stimuli-responsive materials and their interactions with other device components and the surrounding environment is essential.

This review focuses on the most recent advances in the materials science of transient electronics that offer active operation. The article begins with a summary of physical/ chemical mechanisms for transience in this context, from the materials to the devices and the engineered systems. Examples include strategies that exploit triggering events associated with changes in temperature, exposure to solvents/etchants, illumination with light, and delivery of electrical impulses. Although the emphasis is on the underlying materials, the content also includes integration into active (transistor, diode) and passive electrical components (resistor, capacitor, inductor) and implementation at the system level, including associated sub-systems. A concluding section summarizes the current state of the field and highlights some opportunities for further research in material sciences.

STIMULI-RESPONSIVE MATERIALS FOR TRANSIENT ELECTRONICS

In active transient systems, materials degradation and associated operational failure begin only upon the introduction of an external stimulus event as a trigger. In practice, these systems consist of many different types of materials integrated together, where at least one is stimuli responsive. The two main approaches involve (1) response of one of various materials components within a system or (2) disintegration of the entire system through the response of the supporting substrate.







Figure 2. Schematic Illustration of Representative Trigger Stimuli and Failure Mechanisms

Mechanisms can involve heating/cooling or exposing to solvents/etchants, light, or electrical current. A basic understanding of these responses and a means for exploiting them within a device structure represent the core goals. Recent research results provide information on essential properties of various organic/inorganic electronic materials before and after stimulation.^{14–17} The following subsections provide an overview, starting with stimuli-responsive materials and their degradation mechanisms, all in the context of device examples (Figure 2).

Temperature Responsive

This section summarizes thermally responsive materials that decompose or disintegrate directly through heating/cooling. The content also includes modes of active transience mechanism that involve thermal initiation of secondary events. For instance, when the temperature exceeds a certain level, temperature-responsive materials can expand due to the formation of volatile molecules by depolymerization, they can release acidic molecules from a melting process, or their wettability can change from hydrophobic (i.e., insoluble) to hydrophilic (i.e., soluble). Such materials can trigger active transience mechanisms as an interlayer or substrate (1) to disintegrate the device structures or (2) to chemically degrade the devices by causing a secondary event such as release of acidic molecules for etching. These approaches can be useful in circumstances that demand rapid and precisely programmed destruction.

Heating

Thermal stimuli constitute the basis of several approaches to active transience. Figure 3A presents an example in which a thermally decomposable polymer, poly-amethylstyrene (PAMS) responds to impulsive heating via depolymerization.¹⁸ These mechanisms serve as a means for reducing recycling waste for certain chromatography techniques. In one example in transient electronics, the PAMS forms an







Figure 3. Temperature-Triggerable Systems

(A) (Top) Surface morphologies of a device that supports thermally triggered transience by use of poly-**a**-methylstyrene (PAMS) as an interlayer. Scanning electron microscope (SEM) images highlight cracks on the surface of the failed device. (Bottom) The decomposition reaction of PAMS above the critical temperature. Reprinted with permission from Li et al.¹⁸ Copyright 2018, Wiley-VCH.

(B) (Top) Degradation of an array of diodes on a cyclic poly(phthalaldehyde) (cPPA) substrate coated with methanesulfonic acid (MSA)/wax at 55°C. (Bottom) Release of methanesulfonic acid by melting the wax leads to (left) acidic degradation of Mg electrodes and (right) acidic depolymerization of the cPPA. Reprinted with permission from Park et al.²⁰ Copyright 2015, Wiley-VCH.

(C) A microfluidic system with a thermally expandable polymer to initiate chemical dissolution on demand. (Top, left) Schematic illustration of microfluidic channels with a thermally expandable polymer layer and microfabricated heaters. (right) Sequence of optical microscope images associated with dissolution of Si, SiO₂, and Al by triggered release of KOH, KHF, and NaOH etchants, respectively. (Bottom) Schematic illustration of a heat-responsive expandable microsphere. Reprinted with permission from Lee et al.²¹ Copyright 2015, Wiley-VCH.

(D) (Top) Structural separation of Ag nanowire (Ag NW) conductors embedded in methyl cellulose (MC) after cooling. (Bottom) When immersed in a warm water bath ($T_{water} > LCST$), the polymeric binder is hydrophobic and maintains its properties unchanged. The binder becomes hydrophilic and dissolves in a cool water bath ($T_{water} < LCST$). Reprinted with permission from Zhang et al.²² Copyright 2017, American Chemical Society.

interlayer below a based metal-oxide-semiconductor field effect transistor (MOS-FET) that uses a silicon nanomembrane (Si NM) as the semiconductor, where disaggregation into gaseous monomers occurs upon heating to temperatures above



 ${\sim}300^\circ\text{C}$. Free-radical mechanisms in two steps define the kinetics of degradation.¹⁹ Specifically, this thermal process involves random scissions that break the polymer chains at weak points to yield radical chain segments that then depolymerize the remaining material. Released volatile monomers create pressures that fracture the device components by overcoming the ultimate tensile strength of a stress distribution layer.

The versatility of thermal activation can be enhanced when coupled with secondary events accompanied by heat. These events include the release of etchants generated by melting solid materials (serving as a reservoir) or by actuating expandable polymers. For example, as shown in Figure 3B, methanesulfonic acid (MSA) droplets encapsulated in wax ($T_m = 43^{\circ}$ C) can be thermally triggered to (1) etch Mg traces and (2) depolymerize the device substrate, cyclic poly(phthalaldehyde) (cPPA) ($T_c = -40^{\circ}$ C) thereby leading to the destruction of silicon nanomembranes (Si NMs) in positive-intrinsic-negative diodes.²⁰ The transience time depends on the kinetics of both stages of the process, as defined by the concentration of MSA, the applied thermal power, and the thickness of the wax protection layer. The kinetics can be examined as a function of triggering temperature, using Mg resistors as test structures at fixed values for the other parameters (40 wt % of the concentration of MSA, and 14-µm-thick protection layer). Upon heating to 45° C as a thermal trigger event, electrical failure occurs within 10 min. As the temperature rises to 55° C, the performance of the resistor lasts for only 2 min.

Related thermally triggered etching effects can be exploited in microfluidic systems, as shown in Figure 3C.²¹ In this case, a thermally expandable polymer couples to three separately addressable reservoirs filled with a small amount of water and interfaced to microfluidic channels. The thermal actuators consist of microfabricated resistive elements coupled to inductive coils and positioned under the thermally expandable polymers. Maps of temperature collected during wireless operation initiated by proximity to a transmission coil powered with radio frequency power initiate heating to 100°C within 20 s. At this temperature the expandable polymer (\sim 270 μ m thick), which consists of a mixture of polydimethylsiloxane (PDMS) and Expancel (Nouryon) at a ratio of 2:1 by weight, undergoes an irreversible, rapid increase in volume by $\sim 5 \times$, beginning at around 80°C. The functional material in this system (Expancel) adopts a core/shell design where a thermoplastic shell softens above a critical temperature while a liquid hydrocarbon inside undergoes a transition to the gas phase, thereby leading to large volumetric expansion. This expansion serves as a pumping mechanism that drives the flow of water along the microfluidic channels across embedded chemical powders to create active etchants for different types of electronic materials. The specific example highlighted here uses powders of potassium hydroxide (KOH), potassium hydrogen fluoride (K₂HF), and sodium hydroxide (NaOH) for etching of Si, SiO₂ and Al (Al + 4OH⁻ \rightarrow Al(OH)₄⁻ + 3e⁻),²³ respectively, thereby offering functionality across wide-ranging types of electronics. Another example of the use of this class of thermally expandable polymer focuses on mechanical rather than chemical modes of operation. Here, activation of the polymer (~275 µm thick) destroys a thinned silicon chip (25 µm thick) within 10 s for temperatures above 80°C, due to stresses that exceed the fracture limit of the silicon (6.89 GPa).²⁴ According to finite element analysis, this type of operation can be effective for chips with thicknesses as large as 90 μ m.

Cooling

Other thermal effects can also be exploited for active transience. One example uses polymers that exhibit a lower critical solution temperature (LCST)²⁵ such as methyl





cellulose (MC; LCST ~45°C), such that the solubility in water depends strongly on temperature.²² Specifically, for temperatures below the LCST, the polymer becomes hydrophilic. Figure 3D shows a method to exploit this effect, in which Ag nanowires (Ag NWs) embedded in MC release into water to disintegrate an associated circuit within 5 s, upon cooling below the LCST.

Water Responsive

Water can be utilized to trigger the transient process, as described in many fundamental studies of materials that react to water. Although water can serve as a stimulus for triggered transience, for applications in biomedical implants or green electronics, the surrounding environment typically includes water, which leads to passive transient mechanisms. Controlled exposure to solvents or etchants, as in the example of thermally triggered microfluidic release described above, represents one of the most common schemes for active transience, where simple dissolution or chemical reactions in water or aqueous solution often form the basis for transience. In certain cases, an aim is to create platforms in which the conductor, semiconductor, or insulator materials for electrodes, transistors, substrates, or other components react with solvents, most commonly water, including groundwater, biofluids, and others. The same sorts of triggerable microfluidic systems of the previous section can be designed to operate with water alone, instead of traditional etchants. In this context, Mg, Zn, W, Mo, and Fe are attractive conductors because they undergo hydrolysis reactions to yield biocompatible and environmentally safe end products. Although these metals show different detailed behaviors upon immersion in water, they typically react to form metal oxides or hydroxides, some of which are water soluble. Fundamental studies define the kinetics of these processes in thin metal traces as conductors and electrodes.²⁶ The following chemical reactions apply:^{26–30}

 $Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2$

 $Zn + 2H_2O \rightarrow Zn(OH)_2 + H_2$

 $2W + 2H_2O + 3O_2 \rightarrow 2H_2WO_4$

 $2Mo + 2H_2O + 3O_2 \rightarrow 2H_2MoO_4$

$$4\text{Fe} + 3\text{O}_2 + 10\text{H}_2\text{O} \rightarrow 4\text{Fe}(\text{OH})_4^- + 4\text{H}^+$$

The rates of dissolution of thin films (40–300 nm thick) of Mg, Zn, W, and Mo deposited by magnetron sputtering in deionized (DI) water at room temperature, measured as changes in thickness, are ~1,700, 170, 40.8, and 7.2 nm day⁻¹, respectively.³¹ Dissolution of Zn, W, Fe, and Mo in phosphate buffered saline (PBS; pH 7.4) at 37°C occurs at rates of 3,500, 150, 80, and 20 nm day⁻¹, respectively.³² As an example, traces of W can serve as electrical interconnects between components in electronic systems that adopt three-dimensional, heterogeneously integrated formats.³³ Figure 4A summarizes the transient behavior of patterns of W (300 nm thick)





deposited by magnetron sputtering and immersed in PBS at 37°C. Additional examples are Mo and Zn as water-triggerable electrodes (300 nm thick) for electrochemical capacitors³⁴ and conductive pastes, ^{35,36} respectively. Foils of these materials can also be useful, specifically as substrates or as antennas for radio frequency operation, including inductive coils for devices that exploit near-field communication protocols.³ A Mg coil (50 μ m thick) with a diameter of ~15 mm dissolves completely after 14 days in artificial cerebrospinal fluid at 60°C (Figure 4B). Oxides of some of these metals, such as MgO and ZnO, can also undergo hydrolysis, through reactions such as MgO + H₂O \rightarrow Mg(OH)₂ and ZnO + H₂O \rightarrow Zn(OH)₂ or ZnO + H₂O \rightarrow Zn²⁺+2OH⁻.^{2,26} ZnO is particularly interesting as a thin film semiconductor and as a piezoelectric material.

As a semiconductor, silicon is an ideal choice, given its widespread use in conventional electronics and its natural rates of hydrolysis in water to yield biocompatible end products. Specifically, recent studies show that hydrolysis of Si NMs occurs on timescales of days or weeks in physiological conditions.^{2,40,41} The reaction generates orthosilicic acid and H₂ according to Si + 4H₂O \rightarrow Si(OH)₄ + 2H₂, even at near neutral pH conditions.² As an example, a lightly p-doped Si NM (lateral dimension of 3 µm × 3 µm and thickness of 70 nm) dissolves in PBS (pH 7.4) at 37°C at a rate of ~5 nm day⁻¹.² Thus, a 70-nm-thick Si NM completely disappears within 14 days via this mechanism. Other transient silicon-based materials include silicon oxides (e.g., SiO₂) and silicon nitrides (i.e., Si₃N₄), which dissolve according to SiO₂ + H₂O \rightarrow Si(OH)₄^{2,42} and Si₃N₄ + 6H₂O \rightarrow 3SiO₂ + 4NH₃,⁴⁰ respectively. These compounds are important because they are well developed as insulating layers in conventional electronic systems. In all cases, the dissolution kinetics depends on many factors associated with the chemical composition of the solution, the temperature, the pH, and the materials morphology and impurity levels, and others.^{40,43}

Water-soluble Si NMs can serve not only as the essential active material for a variety of transient electronic devices but they can also be used for sensing. As an example, Kim et al.³⁷ describe an array of transient sensors with Si NM electrodes as a dopamine detector. The Si NM electrodes (300 nm thick), heavily doped with boron ($\sim 10^{20}$ cm⁻³), gradually hydrolyze or dissolve within 15 h under accelerated conditions in PBS (10 mM, pH 11) at 37°C, as shown in Figure 4C.

As another example, Si materials form the basis of transient intracranial pressure (ICP) sensors, with lifetimes of several days to weeks, ^{3,44} relevant for monitoring during recovery from traumatic brain injury. The entire platform, from Si NM as a strain sensor to nanoporous Si (NP Si, 60–80 μ m thick; 71% porosity) and SiO₂ (100 μ m thick) as a substrate and a passivation layer, respectively, completely disappears in aqueous buffer solution (pH 12, for accelerated testing) at room temperature after 30 h (Figure 4D).³ The main product of hydrolysis of silicon is ortho-silicic acid (i.e., Si(OH)₄), which has a theoretical solubility of 120 ppm at 25°C (pH 7.4). The amount of Si(OH)₄ present naturally in the human body can be absorbed across the intestinal wall and excreted in the urine. Monomeric silicic acid penetrates all body liquids and tissues at a concentration (~1.7 ppm), significantly less than its solubility. By contrast, polymeric molecules of silicic acid containing up to four to five silicon-oxygen units characterize the form of silicic acid as it transports through the blood.⁴⁵

As alternatives to NP Si, various polymers can be exploited as substrate supports, as well as encapsulation layers and other components of transient systems. Silk fibroin,^{2,38,46} sodium alginate,^{47,48} polyvinyl alcohol (PVA),^{39,49} polyethylene oxide (PEO),⁵⁰ poly(L-lactide-co-glycolide) (PLGA),^{6,51} and elastomeric polymers such as





CellPress





Figure 4. Water-Triggerable Systems

(A and B) SEM (A) and optical (B) images of the dissolution of Mg and W electrodes. Reprinted with permission from Change et al.³³ and Kang et al.³ Copyright, 2018 Wiley-VCH and 2016 Macmillan Publishers.

(C and D) Optical images of the dissolution of electronic sensors that incorporate Si nanomembranes (Si NMs), nanoporous Si (NP Si), and silicon dioxide (SiO₂). Reprinted with permission from Kim et al.³⁷ and Kang et al.³ Copyright, 2018 Wiley-VCH and 2016 Macmillan Publishers.





Figure 4. Continued

(E and F) Optical images of dissolution of systems on a silk (E) and a polyvinyl alcohol (PVA) (F) substrate. Reprinted with permission from Hwang et al.³⁸ and Jin et al.³⁹ Copyright, 2013 Wiley-VCH and 2015 American Chemical Society.

poly(1,8-octanediol-cocitrate) (POC)⁵² and poly(glycerol-co-sebacate) (PGS)⁵³ represent examples of materials for substrates in transient electronics where disintegration occurs upon water stimulation.

Silk fibroin (SF) obtained from *Bombyx mori* (silkworm) cocoons served as substrates for the earliest demonstration of transient electronics.¹ The peptide bonds along the polymer chains in SF are water soluble. Hydrogen bonds that form between hydrogens associated with amide groups and carbonyl oxygens on adjacent chains, together with van der Waals interactions, crosslink the material.⁵⁴ In largely amorphous forms, films of SF with thicknesses of a few micrometers swell and allow water permeation on the timescale of ~1 h (Figure 4E) in deionized (DI) water at room temperature.³⁸ Recrystallization of hydrophobic domains through treatment with alcohol can, however, dramatically lower the permeability to water, thereby reducing the rate of biodegradation in a way that can be controlled over a range of timescales.⁵⁵ After dissolution, the polymer chains degrade into smaller units via hydrolysis of peptide bonds.

Another option is PVA, whose chains include multiple hydroxyl (-OH) groups that enable physical crosslinking (i.e., hydrogen bonds). Upon immersion, hydrogen bonds can form with water molecules that permeate into the polymer network.⁵⁶ As a result, films of these materials swell and dissolve in water. An electronic system built on a substrate of PVA with a thickness of 20 μ m thereby disperses within minutes (Figure 4F).³⁹ The rate of dissolution depends on the degree of crosslinking. Also, increasing the molecular weight decreases the solubility due to inter- and intra-molecular hydrogen bonds that form between the hydroxyl groups of the polymer chains.^{56–58}

Accelerated rates of transience in water-triggered polymer films can be achieved through advanced paths for chemical reaction.⁵⁹ For example, gas-forming agents (sodium bicarbonate [NaHCO₃]/citric acid [C₆H₈O₇]) doped in a water-soluble polymer matrix (Gelatin-PVA [GPVA]/PEO) generate carbon dioxide (CO₂) upon reaction with water. In a simple example of this mechanism, an electrically conductive trace patterned on such a polymer matrix (i.e., GPVA:PEO:NaHCO₃:C₆H₈O₇ = 25:25:12.5:12.5 wt %, calculated over the weight of the ethanol solvent) shows rapid increases in resistance (over three orders of magnitude) within 85 s following a trigger event. Here, the released gas (i.e., CO₂) and the resultant force lead to rapid transience due to the spontaneous dissolution of the polymer substrate. The entire structure undergoes a complete loss of mass after exposure to water for 300 s.

Another concept in triggered transience involves moisture-responsive polymer substrates.⁶⁰ For one such polymer for this purpose, synthesis involves UV-induced polymerization of 4-pentenoic anhydride and poly(ethylene glycol) (PEG) diacrylate with tetrakis(mercaptoacetate). Sensitivity to moisture follows from hydrolysis of the main functional group (i.e., anhydride) to carboxylic acid (-COOH) via exposure to water molecules in ambient air. The degradation kinetics depend on the PEG contents and the humidity. Films with PEG contents of 0% and 10% (molar ratio) require 36 and 48 h to hydrolyze from solid films to viscous liquids, whereas those of 20% and 30% require 48 and 96 h for even partial hydrolysis. At 50%, the effects of hydrolysis are negligible even after 96 h.

CellPress



Figure 5. Light-Triggerable Systems

(A) (Top) Images of degradation of an array of transistors on a photo-acid generator (PAG; MBTT)/cPPA substrate (UV exposure of 379 nm). (Bottom) Chemical reaction associated with photoinduced HCI generation from the PAG/cPPA substrate. This process causes rapid depolymerization of the acid-sensitive cPPA polymer and destruction of the electronics on the substrate. Reprinted with permission from Hernandez et al.⁶¹ Copyright 2014, Wiley-VCH.

(B) Encapsulation design that uses a light-degradable hydrogel in a transient memory device. (Top) Optical images of the photoinduced gel-to-sol transition of a hydrogel and (bottom) associated chemical reactions of crosslinker cleavage. Reprinted with permission from Zhong et al.⁶⁵ Copyright 2018, American Chemical Society.

(C) (Top) Schematic illustration of the degradation of gold following release of photo-initiated cyanide. (Bottom) The dissolution reaction of potassium ferrocyanide in water and subsequent gold cyanidation. Reprinted with permission from Chen et al.⁶⁶ Copyright 2019, Elsevier BV.

Light Responsive

Light-triggerable systems are also possible. Materials with light-triggerable mechanisms can be grouped into three different categories: (1) polymer materials with photo-acid generators (PAGs); (2) light-induced phase transition materials; (3) light-induced degradation of a photo-activated aqueous solution. Integrated light sources such as those based on light-emitting diodes can be used as the trigger mechanisms. For an information security device, UV light can lead to the destruction of memory modules via the action of light-triggerable materials. Most examples rely on metastable polymers blended with PAG additives as substrates and/or encapsulation layers.^{61–63} For transient electronics, these polymers undergo triggered depolymerization reactions that disrupt, disintegrate, and/or dissolve the device components with tunable kinetics.⁶¹ The polymer cPPA is of interest due to its low ceiling temperature ($T_c = -43^{\circ}$ C) and facile synthesis with various end groups. Rapid depolymerization upon backbone bond cleavage is the basis of the use of cPPA as an acid-degradable polymer. Various PAGs, including 2-(4-methoxystyryl)-4,6bis(trichloromethyl)-1,3,5-triazine (MBTT; responsive to 379 nm wavelength),⁶¹ N-hydroxynaphthalimide triflate (HNT; responsive to 254 nm wavelength),⁶⁴ and Rhodorsil Faba (responsive to 365-405 nm wavelength),⁶³ can be used to impart UV light sensitivity. Electronic systems fabricated on composite films of PAG/cPPA exhibit stable performance until triggered transience via exposure to UV light. This process causes the PAG molecules to release reactive Cl⁻ radicals that abstract hydrogens from the environment to form hydrochloric acid (HCl). The HCl reacts with the acetal backbone of cPPA, thereby initiating a process of degradation that leads to the destruction of the electronics by disintegration. Figure 5A shows a free-standing film of 2.5% PAG (MBTT)/cPPA with an array of transistors on its surface before and after exposure to light from a UV lamp (379 nm wavelength) for 230 min.⁶¹ The intensity and the amount of PAG determine the extent and timescale of degradation. Specimens of 5% MBTT/cPPA require \sim 7 min and \sim 15 min to reach failure when exposed to 1.70 mW cm⁻² and 0.70 mW cm⁻², respectively.⁶¹ The sample with 2.5% MBTT fails within 90 min for 0.60 mW cm⁻², while samples with 5% MBTT fail within 35 min at the same illumination.





Hydrogel-oxide bilayer structures can also serve as light-responsive transient materials. Under UV light, the 4-arms-polyethyleneglycol-NH₂ based hydrogel undergoes a gel-to-sol phase transition due to photoinduced cleavage of azo bonds and associated degradation of the three-dimensional network. This process increases the rate of water permeation through the oxide layer.⁶⁵ Figure 5B highlights the complete gel-to-sol phase transition of the hydrogel that follows a crosslinker cleavage reaction initiated by UV light (365 nm wavelength; 300 mW cm⁻² intensity; 80 min). A Mg resistor with the hydrogel-MgO (MgO thickness = 200 nm) bilayer as an encapsulation coating displays stable operation in DI water until exposure to UV light. The illumination of UV light (365 nm wavelength; 300 mW cm⁻² intensity) destroys the three-dimensional network of the hydrogel by a gel-to-sol transition, and the collapse of the network allows water to pass and degrade the MgO protective layer, leading to failure of the Mg resistor within 10 min after illumination.

The dissolution of gold (Au) in cyanide solution represents another scheme for light-triggered transience.⁶⁶ The reaction in this case consists of three steps. First, non-toxic cyanide-containing precursors, including potassium ferricyanide K₃[Fe(CN)₆] and potassium ferrocyanide K₄[Fe(CN)₆], generate cyanide upon illumination with a solar simulator. Second, the resulting free cyanide species diffuse to the surface of the Au. Consequent reactions of Au, known as the Elsner reaction, involve oxygen and water (4Au + 8CN + O_2 + 2H₂O \rightarrow 4[Au(CN)₂] + 4OH). The rate of Au dissolution depends on the pH of the solution and the addition of the heavy metal thallium. Figure 5C illustrates the light-induced dissociation of cyanide and the following dissolution chemistry (i.e., cyanidation) of an Au electrode, which involves an oxidative surface reaction. In this system, 20 s of light illumination (300 W m⁻²) increases the resistance of the Cr/Au layer (2 mm/80 nm) from ~80 Ω to ~140 Ω , corresponding to degradation of the 35-nm-thick Au layer. Although this example uses non-toxic forms of cyanide, such chemistries should be avoided in biomedical or environmental applications.

Other schemes exploit photo-responsive Azo (i.e., 4,4'-didecyloxy-3-methylazobenzene) units to initiate the light-triggered enzymatic reactions.⁶⁷ In one case, a bilayer film of poly-L-lactide (PLLA) coated with Azo and the enzyme of Proteinase K undergoes surface erosion due to a light-induced (365 nm wavelength) phase transition of Azo from solid to liquid^{67,68} that enables enzymatic hydrolysis of the ester bonds. The film of PLLA, with initial thickness of 70 nm, undergoes complete erosion in ~25 min, corresponding to the degradation rate of 2.7 \pm 0.4 nm min⁻¹. This concept can be applied to other biodegradable polymers that include ester functional groups (e.g., polycaprolactone [PCL]), as the basis for substrate or encapsulation strategies.

An alternative light-triggered approach uses absorbance to convert an optical trigger into a thermal trigger. For example, chromophores combined with poly(N-isopropylacrylamide) (PNIPAAM) can induce thermal changes in the swelling capability of PNIPAAMs upon exposure to light.⁶⁹

Electrical Current Responsive

Electrical methods generally provide fast transient behaviors.^{70,71} Often, electrical current triggers generation of chemical energy or release of corrosive chemical agents to dissolve some component parts of the electronics. One example uses an electrically triggerable exothermic energy release layer that consists of Al nanoparticles and poly(4-vinylpyridine)-coated CuO particles. Joule heating or electrical sparking can trigger the ignition of this layer by the following





Figure 6. Electrical Current-Triggerable Systems

(A) (Top) Optical micrographs of the surfaces of chips before (left) and after (right) thermite layer explosion induced by electrical current. (Bottom) Electrical current-triggered exothermic reaction of nanothermite (CuO/Al film). Reprinted with permission from Pandey et al.⁷⁰ Copyright 2018, Wiley-VCH.

(B) (Top) Degradation behavior of an indium gallium zinc oxide (IGZO) field effect transistor (FET) during an electrochemically triggered dissolving process. (Bottom) Schematic illustration of the key steps of the electrical current-triggered transience operation. Reprinted with permission from Sim et al.⁷¹ Copyright 2017, IOP Publishing.

(C) (Top) Degradation of a Si layer via lithiation: SEM images of the surface morphology at (left) 0 h and (right) 12 h. (Bottom) Schematic illustration of the (left) morphological transformation of Li_xSi layers upon lithiation and (right) the exploded view of the device structure for lithiation testing. Reprinted with permission from Chen et al.⁷² Copyright 2019, IOP Publishing.

reaction: $3CuO + 2AI \rightarrow Al_2O_3 + Cu (\Delta H = -604 \text{ kJ mol}^{-1} \text{ of Al}).^{70}$ In examples of silicon chips (supporting electronics or microelectromechanical systems) and metal resistors, a thin film of nanothermite as a substrate can lead to transience times of less than 1 s. Figure 6A shows images of a representative chip after this process, both with (left) and without (right) charred residues remaining on top.

Another electrical triggering approach relies on corrosive chemical agents in sealed reservoirs and placed over device platforms that also support a source of power, such as a Joule heating element or an electrochemical reactor. Triggering opens the reservoirs to initiate the transience process.^{70,71} The operation of an example of an electrochemical reactor is in Figure 6B (bottom). Application of a DC voltage between a pair of electrodes electrolyzes the etching solution to generate gases that lead to an increase in pressure. Above a critical level, this pressure fractures a sealing membrane to release the etching solution from the reservoir to the electronics. Fast transience follows from chemical dissolution.⁷¹ Images of the electronics, based on indium gallium zinc oxide (IGZO) as the semiconductor, Cu as the conductor, MgO as the dielectric, and glass substrate, are in Figure 6B (top). Triggering with a 5 V DC voltage fractures a Si₃N₄ membrane to release a corrosive solution (a mixture of copper etchant and NaCl solution; volume ratio = 1:9) that etches key components of the device, such as the Cu gate electrode, MgO dielectric, IGZO channel, and Cu source/drain electrodes to the point of operational failure within 15 s. Complete dissolution of the field effect transistor (FET) occurs within additional tens of seconds.

One challenge with these types of approaches is in the long-term, stable storage of exothermic energy release agents or chemical etchants. An alternative strategy for electrically triggered systems that avoids this limitation is based on the lithiation of Si.⁷² Figure 6C (bottom, left) illustrates the mechanism. Lithium electrochemically inserts into the Si through a galvanostatic mode at a constant current density. A vein-like network of Li_xSi forms beneath a planar layer of Li_xSi. The accumulated stresses associated with this lithium diffusion-induced process cause the formation of microcracks in the Si samples. These microcracks create fast paths for lithium diffusion,





Figure 7. Overview of Stimuli-Responsive Materials for Transient Electronics

In water-responsive materials, filled and empty marks correspond to room and body temperature, respectively.

leading to the accelerated penetration of the vein-like Li_xSi network and fracture of the Si membranes. Figure 6C (bottom, right) shows an exploded view of a test structure built with a thin Si integrated circuit chip. A hole with a diameter of 10 mm on the positive case of the CR2032 coin cell covered by a thin piece of glass (20 mm in diameter, 500 μ m in thickness) and sealed on the edge defines an observation window. A PDMS stamp with Si ribbons firmly adheres to the glass. A thin layer of Au (200 nm) deposited on the edge of Si ribbons, PDMS substrate, and the glass allows electrical connection to the case. Assembly of other components used in the CR2032 coin cell (including the separator, lithium counter electrode, spacer, spring, and the negative case) completes a functional test device. Figure 6C (top) shows that the Si ribbons fragment into microscale pieces after 12 h of lithiation (current density of 400 μ A cm⁻²).

Figure 7 summarizes the main classes of stimuli-responsive materials along with the type of stimulus and the time to functional failure after a triggering event (degradation time). Materials that respond to electrical current and temperature (cooling and heating) often provide the shortest degradation times, in the range of seconds to minutes, with the potential for additional reductions through engineering optimization. In most cases, light-responsive materials lead to degradation times that are longer than those of electrical or thermally triggered systems. For instance, reports indicate that PAGs (e.g., MBTT) involve times in the range of tens to hundreds of minutes, ⁶¹ depending on the concentration, the detailed chemistry, and the intensity





Figure 8. Triggered Transient Devices Based on Various Stimuli

(A) Light-triggerable memory device. (Top) Schematic illustration of a light-responsive hydrogelencapsulated resistive random access memory (RRAM) (W/MgO/Mg) and optical images of the 3 × 3 transient RRAM crossbar array. (Bottom) Changes in resistance indicate controllable degradation of RRAM by exposure to UV light. Reprinted with permission from Zhong et al.⁶⁵ Copyright 2018, American Chemical Society.

(B) Heat-triggerable FET. (Top) Schematic illustration of a Si NM FET in an exploded view format. Inset shows a photograph of an array of such FETs. (Bottom) Temperature-dependent transfer characteristics of a Si NM FET on PAMS. The inset shows the electrical characteristics of the device after heated to 300°C for 3 min. Reprinted with permission from Li et al.¹⁸ Copyright 2018, Wiley-VCH.

(C) Water-triggerable capacitor. (Top) Optical images corresponding to the time-sequential dissolution of the capacitors (Cu/MgO/Cu) after (left) 0 h and (right) 84 h in an environment with humidity of 75%. (Bottom) Changes in the (black) capacitance and (red) dielectric loss of a transient





Figure 8. Continued

capacitor as a function of time of exposure to a humid environment. Reprinted with permission from Gao et al.⁶⁰ Copyright 2017, AAAS.

(D) Components for radio frequency (RF) communication with a heat-triggerable microfluidic system. (Top, left) Inductor RF device designed to transform via dissolution of Mg and AI traces that act as electrical shorts in a planar spiral coil. (Top, right) Magnified views of the crossover lines at several stages during triggered transformation. (Bottom) Reduction in the resonance frequency upon dissolution of the AI and Mg sequentially after heat-triggered release of corrosive etchants. Reprinted with permission from Lee et al.⁷⁸ Copyright 2015, Wiley-VCH.

of light. A variety of water-responsive materials support degradation times from seconds to weeks. This category includes conductors, semiconductors, and insulators, and thus can be exploited in transient devices/systems such as electrodes, transistor channels, dielectric layers, substrates, passivation layers, and others. Most waterresponsive materials degrade slowly over timescales that increase with the thicknesses of the responsive layers.

TRIGGERED TRANSIENT DEVICES

Many different types of active transient devices and systems can be constructed using the materials and principles described in the previous sections. The following content summarizes some examples, with an emphasis on those that rely critically on active triggers in their operation. For instance, rapid progress in data storage technologies coupled with the proliferation of smart devices creates challenges in information security. Although encryption schemes and associated software approaches are important, hardware-based mechanisms provide the ultimate level of security. In this context, triggered transient devices based on stimuli-responsive materials could offer important options through self-destructive and/or irreversible elimination of function in data storage components.

The memory modules themselves can be fabricated from or integrated with stimuliresponsive materials. Figure 8A shows an example in the form of 3 × 3 arrays of transient resistive random access memory (RRAM) elements fabricated with water-soluble electrodes (Mg, W) and dielectrics (MgO), using an encapsulation approach based on a light-responsive hydrogel-MgO (200 nm) bilayer. The RRAM shows stable memory function with reliable on ($10^2 \Omega$) and off ($10^6 \Omega$) switching, during the first ~10 min after UV illumination. After 12 min of illumination, the resistance reaches $10^{12} \Omega$, and the module loses its memory function due to the hydrolysis of device materials by water that permeates through the encapsulation according to mechanisms described previously.^{73–75} Similarly, water-soluble solid sodium glycerin or heatresponsive polyoxymethylene (POM) substrates support other forms of stimuli-triggered destruction of these or related data storage devices.^{76,77}

As another option, the transistor elements in data storage devices can be constructed with triggered transient behavior by integration with stimuli-responsive substrates. One example (Figure 8B) is in the multilayer configuration of an MOSFET, where SiO₂ (~2 μ m thick) serves as an encapsulation layer to a Si NM (active layer, 340 nm thick). A bilayer of SiO₂/Al₂O₃ (70/13 nm thick) defines the gate dielectric layer, with Cr/Au (5/100 nm thick) electrodes as source, drain, and gate. PAMS as an interlayer lies beneath the layer of Cr/Au electrodes to enable destruction of the Si NM MOSFET for temperatures at or above its decomposition temperature, as previously discussed. Polydimethylsiloxane (PDMS, ~5 μ m thick) serves as an adhesive layer between polyimide (PI, ~5 μ m thick) and a flexible Kapton substrate (~12.5 μ m thick). Temperatures that exceed the decomposition temperature of the PAMS interlayer (~300°C for 3 min) lead to severe fragmentation of the SiO₂



Table 1. Recent Demonstrations in Active, Transient Devices

Device	Stimuli	Major Failure Material (Role in Device; Thickness)	Failure Mechanism	Complete Destruction Time (Failure Time)	Reference
Transistor	Heat	PAMS (interlayer; 4 μm)	Volume expansion (at 300°C)	3 min	Li et al. ¹⁸ 2018
		Expancel/PDMS (interlayer; 270 μm)	 Volume expansion (at>80°C) Corrosion 	10 s	Lee et al. ²¹ 2015
		Nitrocellulose paper (substrate; 82 µm)	Burning (at 250°C)	2.8 s	Yoon et al. ⁸⁰ 2017
		Cyclododecane (substrate; 4– 5 mm)	Sublimation (at 60°C)	3–12 days	Kim et al. ⁸¹ 2017
	Light	MBTT in cPPA (substrate; 40 μm)	 Photo-acid generation (UV 379 nm) Depolymerization 	5% MBTT: 20 min 2.5% MBTT: 230 min (110 min)	Lopez Hernandez et al. ⁶¹ 2014
	Electrical current	Acidic agent (gas formation), Si_3N_4 (membrane)	 Electrolysis (V_{DC} 5 V) Membrane fracture 	<60 s	Sim et al. ⁷¹ 2017
		Si (channel; ~5 μm)	Lithiation (400 μ A/cm ²)	6–12 h	Chen et al. ⁷² 2019
Diode	Heat	Methanesulfonic acid/wax cPPA (substrate; 45 μm)	 Melting (at 55°C) Acidic dissolution 	1 min (20 s)	Park et al. ²⁰ 2015
		Poly(ε-caprolactone) (substrate; 120 μm)	Melting (at 90°C)	2 s	Gao et al. ⁸³ 2017
Capacitor	Heat	Cyclododecane (dielectric; 70– 100 µm)	Sublimation (at 60°C)	3–12 days (60 h)	Kim et al. ⁸¹ 2017
	Cooling	Methyl cellulose (dielectric; 110 μm)	Wettability change (from 60°C to 22°C)	5 min	Zhang and Bellan ²² 2017
Memory devices	Heat	Polyoxymethylene (substrate; 1 mm)	Depolymerization (at 180°C)	42 min (8 min)	Liu et al. ⁷⁶ 2019
	Light	Cross-linked PEG-NH ₂ with thermo-degradable linker (packaging; 3–10 mm), MgO (encapsulant; 200 nm)	 Chain scission (UV 365 nm, 300 mW·cm⁻²) Hydrolysis at room temper- ature 	24 h (10 min)	Zhong et al. ⁶⁵ 2018
Generator	Light	Cyclic poly(phthalaldehyde) (substrate; 100 μm)	 Photo-acid generation (UV 365 nm, 4 mW ⋅ cm⁻²) Depolymerization 	5 min (2 min)	Wu et al. ⁶³ 2019
Antenna	Heat	Expancel/PDMS (interlayer; 300 µm)	 Volume expansion (at 80°C) Corrosion 	N/A	Lee et al. ⁷⁸ 2015
	Cooling	Elastin-like peptide (substrate, encapsulant; N/A)	Wettability change (at 6.17°C)	160 s	Lin et al. ⁸⁴ 2019
		Methyl cellulose (substrate/ encapsulant; 40 μm)	Wettability change (at 37°C)	N/A (5 min)	Zhang et al. ⁸⁵ 2019

Dagdeviren et al.,⁴⁶ Lee et al.,⁸⁶ Jiang et al.,⁸⁷ Yin et al.,⁸⁸ Lu et al.,⁸⁹ Lei et al.,⁹⁰ Kim et al.,⁹¹ and Hosseini et al.⁹²

and Si NM, thereby physically destroying the MOSFET.¹⁸ Various other means for physical destruction exploit water-soluble polymers (PVA,⁴⁹ PLGA⁷⁹), photo-responsive acid generators (cPPA),⁶¹ flammable (nitrocellulose [NC]),⁸⁰ and sublimating (cyclododecane)⁸¹ materials.

Capacitors, as additional building block elements of solid-state memory modules, can also be fabricated in transient forms. One case uses a capacitor with Cu as the top and bottom electrodes and MgO as an insulator on a water-responsive polyan-hydride (~124 μ m thick) substrate (Figure 8C).⁶⁰ The polyanhydride film can generate carboxylic acid after hydrolysis of the anhydride group. Thus, the Cu (50 nm thick) and MgO (50 nm thick) placed on a polyanhydride substrate undergo acidic dissolution at a relative humidity of ~75%, according to the following mechanism: M (MO_x) + 2RCOOH \rightarrow 2RCO⁻ + M^{y+} + H₂ (H₂O) and loss of function (an





initial capacitance of \sim 125 pF) at a frequency of 100 Hz within 30 h. No changes occur at humidity levels near 0%.

Additional examples are in transient components for radio frequency (RF) communication, such as antennas. One case exploits wirelessly controlled microfluidic devices that support triggered release of etching solutions (water for Mg and NaOH for Al) designed to shift the resonance frequency of such an antenna (Au, 800 nm thick) (Figure 8D), initially configured to operate at 233 MHz. Upon a trigger, etching solutions pass through microchannels to selectively dissolve electrode traces (i.e., Mg, Al) that connect certain parts of the Au antenna structure, such that their removal increases the number of turns of the antenna. Since the frequency of the antenna is inversely proportional to the number of turns of coil in the loop, this process increases the frequency from 233 MHz to 222 MHz and 173 MHz due to chemical dissolution of Mg (2 µm thick) and Al (1 µm thick) traces.⁷⁸ Similarly, Gumus et al.⁸² demonstrate a wirelessly destructible form of Si electronics that incorporates a global positioning system [GPS] and light and pressure sensors. The failure mechanism follows from mechanical destruction of a thin Si layer (25 µm thick) on an expandable polymer (i.e., Expancel) by thermal trigger, as described in a previous section. The GPS sensor allows for automatic destruction if the system moves outside a certain perimeter of coordinates. Furthermore, the destruction can be triggered when the illumination or the pressure exceeds a predefined threshold measured by the light or pressure sensor, respectively.

Table 1 provides an overview of triggered transient devices based on various stimuliresponsive materials.

CONCLUSIONS AND PERSPECTIVES

Since the first report on transient devices in 2009, this field of scientific study and engineering development has experienced significant growth to include a wide variety of materials that respond to external physical and chemical stimuli, as well as their use in unique systems with functions to address applications outside of those contemplated by conventional permanent devices. Depending on the stimuliresponsive materials and the layouts, the timescales for transience can range from seconds to days. Although most recently reported research on transient electronics focuses on passive transient mechanisms, sophisticated, precise approaches that enable active or triggered transience are of high interest.

In addition to programmable microfluidic systems for controlled release of etchants, tailored substrates or encapsulation layers can serve as the basis for this type of active operation. In the simplest cases, reliable performance of the transient system persists until the encapsulation material is compromised by, for example, hydrolysis by exposure to water. Organic polymers (e.g., polyanhydride)⁹³ with hydrophobic properties or inorganic materials (e.g., SiO₂, Si₃N₄) are well suited for these roles.^{40,42} Controlling their behaviors as water barriers is a key feature that defines the lifetime of entire system. As a result, advances in encapsulation materials and strategies, including those that consider the geometrical structures and layouts, will continue to be important.

Transience mechanisms triggered by electrical current, thermal effects, or optical effects are of interest partly because they can support fast responses. A limitation is that such approaches are often not well suited to applications in biomedical devices.⁹⁴ Specifically, heat and electrical current can introduce off-target negative



effects on surrounding tissues, and magnetic fields can interfere with medical imaging techniques, and the range of acceptable pH is defined by physiological values. For these reasons, dissolution or destruction by water-based stimulus (i.e., biofluid) is advantageous in biomedical systems. By contrast, military and industrial applications require immediate failure and non-recoverable designs for strong information security, without the constraints mentioned above.

Hybrid stimuli can create additional opportunities in advanced applications. Cascade-based triggering processes that use multiple stimuli applied sequentially in time add versatility and create unusual design options. Here, an engineered combination of materials and device structures exploits two or more reactions, where initiation of the first becomes a stimulus for the second. Such dual stimuli can support improved levels of specificity in their response. For example, sudden illumination of light-triggerable systems can lead to unwanted functional impairment. Encapsulating a system with materials that change from opaque to transparent in response to a stimulus (e.g., heating) other than light can prevent the system from responding to light until presented with this stimulus. Here and in other cases, specialized materials that respond to ultrasound, magnetic field, and electric field, some based on shape memory polymers as demonstrated in actuators and drug delivery systems, ^{95–97} have the potential to be useful in transient electronic systems with modes of triggering different from those summarized here.

Recent advances in materials and responsive mechanisms to modulate the processes of active transience via engineering design accompanied by chemical/mechanical failure may be practical in this context. Continued efforts in precise triggering of the system (i.e., active transience) and associated flexible control over the operational lifetime will lead to powerful capabilities. Triggering techniques require consideration of all aspects of materials, mechanics, and geometry. Research directions for this field include development of (1) thermally, electrically, electrochemically, optically, and mechanically responsive materials, (2) material/chemical engineering modifications for improved sensitivity to the triggering events, and (3) systematic stimulus arrangements for transient systems via cascade or hybrid triggering. The diverse materials science and materials engineering content creates many opportunities for basic and applied studies.

ACKNOWLEDGMENTS

This work was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2019R1A6A3A03033055).

AUTHOR CONTRIBUTIONS

Conceptualization, G.L., Y.S.C., H.-J.Y., and J.A.R.; Investigation, G.L., Y.S.C., and H.-J.Y.; Writing – Original Draft, G.L., Y.S.C., and H.-J.Y.; Writing – Review & Editing, G.L., Y.S.C., H.-J.Y., and J.A.R.; Organization & Design (Figure), G.L.; Supervision, J.A.R.

REFERENCES

- Kim, D.-H., Kim, Y.-S., Amsden, J., Panilaitis, B., Kaplan, D.L., Omenetto, F.G., Zakin, M.R., and Rogers, J.A. (2009). Silicon electronics on silk as a path to bioresorbable, implantable devices. Appl. Phys. Lett. 95, 133701.
- Hwang, S.-W., Tao, H., Kim, D.-H., Cheng, H., Song, J.-K., Rill, E., Brenckle, M.A., Panilaitis, B., Won, S.M., Kim, Y.-S., et al. (2012). A physically transient form of silicon electronics. Science 337, 1640–1644.
- Kang, S.K., Murphy, R.K.J., Hwang, S.W., Lee, S.M.S.H., Harburg, D.V., Krueger, N.A., Shin, J., Gamble, P., Cheng, H., Yu, S., et al. (2016). Bioresorbable silicon electronic sensors for the brain. Nature 530, 71–76.

CellPress

- Yu, K.J., Kuzum, D., Hwang, S.W., Kim, B.H., Juul, H., Kim, N.H., Won, S.M., Chiang, K., Trumpis, M., Richardson, A.G., et al. (2016). Bioresorbable silicon electronics for transient spatiotemporal mapping of electrical activity from the cerebral cortex. Nat. Mater. 15, 782–791.
- Boutry, C.M., Kaizawa, Y., Schroeder, B.C., Chortos, A., Legrand, A., Wang, Z., Chang, J., Fox, P., and Bao, Z. (2018). A stretchable and biodegradable strain and pressure sensor for orthopaedic application. Nat. Electron. 1, 314–321.
- Koo, J., MacEwan, M.R., Kang, S.-K.K., Won, S.M., Stephen, M., Gamble, P., Xie, Z., Yan, Y., Chen, Y.-Y.Y., Shin, J., et al. (2018). Wireless bioresorbable electronic system enables sustained nonpharmacological neuroregenerative therapy. Nat. Med. 24, 1830–1836.
- Wallace, H., Basehore, B., and Zito, P. (2020). Wound Healing Phases (StatPearls). https:// www.ncbi.nlm.nih.gov/books/NBK470443/.
- Terazono, A., Murakami, S., Abe, N., Inanc, B., Moriguchi, Y., Sakai, S.I., Kojima, M., Yoshida, A., Li, J., Yang, J., et al. (2006). Current status and research on E-waste issues in Asia. J. Mater. Cycles Waste Manag. 8, 1–12.
- Shinkuma, T., and Minh Huong, N.T. (2009). The flow of E-waste material in the Asian region and a reconsideration of international trade policies on E-waste. Environ. Impact Assess. Rev. 29, 25–31.
- Tsydenova, O., and Bengtsson, M. (2011). Chemical hazards associated with treatment of waste electrical and electronic equipment. Waste Manag. 31, 45–58.
- Luo, C., Liu, C., Wang, Y., Liu, X., Li, F., Zhang, G., and Li, X. (2011). Heavy metal contamination in soils and vegetables near an e-waste processing site, south China. J. Hazard. Mater. 186, 481–490.
- Jin, I.K., Park, J.Y., Lee, B.H., Jeon, S.B., Tcho, I.W., Park, S.J., Kim, W.G., Han, J.K., Lee, S.W., Kim, S.Y., et al. (2018). Self-powered data erasing of nanoscale flash memory by triboelectricity. Nano Energy 52, 63–70.
- Banerjee, N., Xie, Y., Rahman, M.M., Kim, H., and Mastrangelo, C.H. (2014). From chips to dust: the MEMS shatter secure chip. 2014 IEEE 27th International Conference on Micro Electro Mechanical Systems (MEMS), San Francisco, CA (IEEE), pp. 1123–1126.
- Stuart, M.A.C., Huck, W.T.S., Genzer, J., Müller, M., Ober, C., Stamm, M., Sukhorukov, G.B., Szleifer, I., Tsukruk, V.V., Urban, M., et al. (2010). Emerging applications of stimuli-responsive polymer materials. Nat. Mater. 9, 101–113.
- Wei, M., Gao, Y., Li, X., and Serpe, M.J. (2017). Stimuli-responsive polymers and their applications. Polym. Chem. 8, 127–143.
- Choi, Y.S., Koo, J., and Rogers, J.A. (2020). Inorganic materials for transient electronics in biomedical applications. MRS Bull. 45, 103–112.
- Khan, F., and Tanaka, M. (2018). Designing smart biomaterials for tissue engineering. Int. J. Mol. Sci. 19, 1–14.

- Li, G., Song, E., Huang, G., Guo, Q., Ma, F., Zhou, B., and Mei, Y. (2018). High-temperaturetriggered thermally degradable electronics based on flexible silicon nanomembranes. Adv. Funct. Mater. 28, 1801448.
- Malhotra, S.L., Baillet, C., Minh, L., and Blanchard, L.P. (1978). Thermal decomposition of poly-*a*-methylstyrene. J. Macromol. Sci. A Chem. 12, 129–147.
- Park, C.W., Kang, S.K., Hernandez, H.L., Kaitz, J.A., Wie, D.S., Shin, J., Lee, O.P., Sottos, N.R., Moore, J.S., Rogers, J.A., and White, S.R. (2015). Thermally triggered degradation of transient electronic devices. Adv. Mater. 27, 3783–3788.
- Lee, C.H., Jeong, J.W., Liu, Y., Zhang, Y., Shi, Y., Kang, S.K., Kim, J.S.J., Kim, J.S.J., Lee, N.Y., Kim, B.H., et al. (2015). Materials and wireless microfluidic systems for electronics capable of chemical dissolution on demand. Adv. Funct. Mater. 25, 1338–1343.
- Zhang, X., and Bellan, L.M. (2017). Composites formed from thermoresponsive polymers and conductive nanowires for transient electronic systems. ACS Appl. Mater. Interfaces 9, 21991– 21997.
- Boukerche, I., Djerad, S., Benmansour, L., Tifouti, L., and Saleh, K. (2014). Degradability of aluminum in acidic and alkaline solutions. Corros. Sci. 78, 343–352.
- Webb, W.W., and Forgeng, W.D. (1958). Mechanical behavior of microcrystals. Acta Metall. 6, 462–469.
- Zhang, Q., Weber, C., Schubert, U.S., and Hoogenboom, R. (2017). Thermoresponsive polymers with lower critical solution temperature: from fundamental aspects and measuring techniques to recommended turbidimetry conditions. Mater. Horiz. 4, 109–116.
- 26. Yin, L., Cheng, H., Mao, S., Haasch, R., Liu, Y., Xie, X., Hwang, S.W., Jain, H., Kang, S.K., Su, Y., et al. (2014). Dissolvable metals for transient electronics. Adv. Funct. Mater. 24, 645–658.
- Kirkland, N.T., Birbilis, N., and Staiger, M.P. (2012). Assessing the corrosion of biodegradable magnesium implants: a critical review of current methodologies and their limitations. Acta Biomater. 8, 925–936.
- Patrick, E., Orazem, M.E., Sanchez, J.C., and Nishida, T. (2011). Corrosion of tungsten microelectrodes used in neural recording applications. J. Neurosci. Methods 198, 158–171.
- Badawy, W.A., and Al-Kharafi, F.M. (1998). Corrosion and passivation behaviors of molybdenum in aqueous solutions of different pH. Electrochim. Acta 44, 693–702.
- Stefánsson, A. (2007). Iron(III) hydrolysis and solubility at 25°C. Environ. Sci. Technol. 41, 6117–6123.
- Li, R., Wang, L., and Yin, L. (2018). Materials and devices for biodegradable and soft biomedical electronics. Materials (Basel) 11, 2108.
- Kang, S.K., Hwang, S.W., Yu, S., Seo, J.H., Corbin, E.A., Shin, J., Wie, D.S., Bashir, R., Ma, Z., and Rogers, J.A. (2015). Biodegradable thin metal foils and spin-on glass materials for

transient electronics. Adv. Funct. Mater. 25, 1789–1797.

Matter Review

- Chang, J.-K., Chang, H.-P., Guo, Q., Koo, J., Wu, C.-I., and Rogers, J.A. (2018). Biodegradable electronic systems in 3D, heterogeneously integrated formats. Adv. Mater. 30, 1704955.
- Lee, G., Kang, S.-K., Won, S.M., Gutruf, P., Jeong, Y.R., Koo, J., Lee, S.-S., Rogers, J.A., and Ha, J.S. (2017). Fully biodegradable microsupercapacitor for power storage in transient electronics. Adv. Energy Mater. 7, 1700157.
- Lee, Y.K., Kim, J., Kim, Y., Kwak, J.W., Yoon, Y., and Rogers, J.A. (2017). Room temperature electrochemical sintering of Zn microparticles and its use in printable conducting inks for bioresorbable electronics. Adv. Mater. 29, 1702665.
- Li, J., Luo, S., Liu, J., Xu, H., and Huang, X. (2018). Processing techniques for bioresorbable nanoparticles in fabricating flexible conductive interconnects. Materials (Basel) 11, 1102.
- Kim, H.-S., Yang, S.M., Jang, T.-M., Oh, N., Kim, H.-S., and Hwang, S.-W. (2018). Bioresorbable silicon nanomembranes and iron catalyst nanoparticles for flexible, transient electrochemical dopamine monitors. Adv. Healthc. Mater. 7, 1801071.
- Hwang, S.W., Huang, X., Seo, J.H., Song, J.K., Kim, S., Hage-Ali, S., Chung, H.J., Tao, H., Omenetto, F.G., Ma, Z., and Rogers, J.A. (2013). Materials for bioresorbable radio frequency electronics. Adv. Mater. 25, 3526– 3531.
- 39. Jin, S.H., Kang, S.K., Cho, I.T., Han, S.Y., Chung, H.U., Lee, D.J., Shin, J., Baek, G.W., Kim, T. II, Lee, J.H., and Rogers, J.A. (2015). Watersoluble thin film transistors and circuits based on amorphous indium-gallium-zinc oxide. ACS Appl. Mater. Interfaces 7, 8268–8274.
- Kang, S.K., Hwang, S.W., Cheng, H., Yu, S., Kim, B.H., Kim, J.H., Huang, Y., and Rogers, J.A. (2014). Dissolution behaviors and applications of silicon oxides and nitrides in transient electronics. Adv. Funct. Mater. 24, 4427–4434.
- Yin, L., Farimani, A.B., Min, K., Vishal, N., Lam, J., Lee, Y.K., Aluru, N.R., and Rogers, J.A. (2015). Mechanisms for hydrolysis of silicon nanomembranes as used in bioresorbable electronics. Adv. Mater. 27, 1857–1864.
- 42. Lee, Y.K., Yu, K.J., Kim, Y., Yoon, Y., Xie, Z., Song, E., Luan, H., Feng, X., Huang, Y., and Rogers, J.A. (2017). Kinetics and chemistry of hydrolysis of ultrathin, thermally grown layers of silicon oxide as biofluid barriers in flexible electronic systems. ACS Appl. Mater. Interfaces 9, 42633–42638.
- 43. Hwang, S.W., Park, G., Edwards, C., Corbin, E.A., Kang, S.K., Cheng, H., Song, J.K., Kim, J.H.J., Yu, S., Ng, J., et al. (2014). Dissolution chemistry and biocompatibility of singlecrystalline silicon nanomembranes and associated materials for transient electronics. ACS Nano 8, 5843–5851.
- 44. Shin, J., Yan, Y., Bai, W., Xue, Y., Gamble, P., Tian, L., Kandela, I., Haney, C.R., Spees, W., Lee, Y., et al. (2019). Bioresorbable pressure sensors protected with thermally grown silicon

Matter Review

dioxide for the monitoring of chronic diseases and healing processes. Nat. Biomed. Eng. 3, 37–46.

- Ducheyne, P., Healy, K., Hutmacher, D.W., Grainger, D.W., and Kirkpatrick, C.J. (2015). Comprehensive Biomaterials (Elsevier Science).
- Dagdeviren, C., Hwang, S.W., Su, Y., Kim, S., Cheng, H., Gur, O., Haney, R., Omenetto, F.G., Huang, Y., and Rogers, J.A. (2013). Transient, biocompatible electronics and energy harvesters based on ZnO. Small 9, 3398–3404.
- Fu, K., Liu, Z., Yao, Y., Wang, Z., Zhao, B., Luo, W., Dai, J., Lacey, S.D., Zhou, L., Shen, F., et al. (2015). Transient rechargeable batteries triggered by cascade reactions. Nano Lett. 15, 4664–4671.
- Hu, W., Jiang, J., Xie, D., Wang, S., Bi, K., Duan, H., Yang, J., and He, J. (2018). Transient security transistors self-supported on biodegradable natural-polymer membranes for brain-inspired neuromorphic applications. Nanoscale 10, 14893–14901.
- Yoon, J., Han, J., Choi, B., Lee, Y., Kim, Y., Park, J., Lim, M., Kang, M.H., Kim, D.H., Kim, D.M., et al. (2018). Three-dimensional printed poly(vinyl alcohol) substrate with controlled ondemand degradation for transient electronics. ACS Nano 12, 6006–6012.
- Chen, Y., Jamshidi, R., and Montazami, R. (2020). Study of partially transient organic epidermal sensors. Materials (Basel) 13, 1112.
- Hwang, S.W., Song, J.K., Huang, X., Cheng, H., Kang, S.K., Kim, B.H., Kim, J.H., Yu, S., Huang, Y., and Rogers, J.A. (2014). High-performance biodegradable/transient electronics on biodegradable polymers. Adv. Mater. 26, 3905–3911.
- 52. Hwang, S.W., Lee, C.H., Cheng, H., Jeong, J.W., Kang, S.K., Kim, J.H., Shin, J., Yang, J., Liu, Z., Ameer, G.A., et al. (2015). Biodegradable elastomers and silicon nanomembranes/ nanoribbons for stretchable, transient electronics, and biosensors. Nano Lett. 15, 2801–2808.
- Boutry, C.M., Nguyen, A., Lawal, Q.O., Chortos, A., Rondeau-Gagné, S., and Bao, Z. (2015). A sensitive and biodegradable pressure sensor array for cardiovascular monitoring. Adv. Mater. 27, 6954–6961.
- Murphy, A.R., and Kaplan, D.L. (2009). Biomedical applications of chemicallymodified silk fibroin. J. Mater. Chem. 19, 6443– 6450.
- Wang, Y., Rudym, D.D., Walsh, A., Abrahamsen, L., Kim, H.-J., Kim, H.S., Kirker-Head, C., and Kaplan, D.L. (2008). In vivo degradation of three-dimensional silk fibroin scaffolds. Biomaterials 29, 3415–3428.
- 56. Harpaz, D., Axelrod, T., Yitian, L.A., Eltzov, E., Marks, S.R., and Tok, I.Y.A. (2019). Dissolvable polyvinyl-alcohol film, a time-Barrier to modulate sample flow in a 3D-printed holder for capillary flow paper diagnostics. Materials (Basel) 12, 343.
- S.W. Shalaby, C.L. MacCormick, and G.B. Butler, eds. (1992). Water-Soluble Polymers: Synthesis, Solution Properties, and

Applications (American Chemical Society), ACS Symposium 467.

- Chan, L.W., Hao, J.S., and Heng, P.W.S. (1999). Evaluation of permeability and mechanical properties of composite polyvinyl alcohol films. Chem. Pharm. Bull. (Tokyo) 47, 1412–1416.
- Jamshidi, R., Chen, Y., and Montazami, R. (2020). Active transiency: a novel approach to expedite degradation in transient electronics. Materials (Basel) 13, 1514.
- Gao, Y., Zhang, Y., Wang, X., Sim, K., Liu, J., Chen, J., Feng, X., Xu, H., and Yu, C. (2017). Moisture-triggered physically transient electronics. Sci. Adv. 3, 1701222.
- Lopez Hernandez, H., Kang, S.K., Lee, O.P., Hwang, S.W., Kaitz, J.A., Inci, B., Park, C.W., Chung, S., Sottos, N.R., Moore, J.S., et al. (2014). Triggered transience of metastable poly(phthalaldehyde) for transient electronics. Adv. Mater. 26, 7637–7642.
- 62. Gourdin, G., Phillips, O., Schwartz, J., Engler, A., and Kohl, P. (2017). Phototriggerable, fully transient electronics: component and device fabrication. 2017 IEEE 67th Electronic Components and Technology Conference (ECTC), Orlando, FL (IEEE), pp. 190–196.
- 63. Wu, C., Jiang, J., Guo, H., Pu, X., Liu, L., Ding, W., Kohl, P.A., and Wang, Z.L. (2019). Sunlighttriggerable transient energy harvester and sensors based on triboelectric nanogenerator using acid-sensitive poly(phthalaldehyde). Adv. Electron. Mater. 5, 1900725.
- 64. Shi, C., Leonardi, A., Zhang, Y., Ohlendorf, P., Ruyack, A., Lal, A., and Ober, C.K. (2018). UVtriggered transient electrospun poly(propylene carbonate)/Poly(phthalaldehyde) polymer blend fiber mats. ACS Appl. Mater. Interfaces 10, 28928–28935.
- 65. Zhong, S., Ji, X., Song, L., Zhang, Y., and Zhao, R. (2018). Enabling transient electronics with degradation on demand via light-responsive encapsulation of a hydrogel-oxide bilayer. ACS Appl. Mater. Interfaces 10, 36171–36176.
- 66. Chen, W.D., Kang, S.K., Stark, W.J., Rogers, J.A., and Grass, R.N. (2019). The light triggered dissolution of gold wires using potassium ferrocyanide solutions enables cumulative illumination sensing. Sensors Actuators B Chem. 282, 52–59.
- Kikkawa, Y., Tanaka, S., and Norikane, Y. (2017). Photo-triggered enzymatic degradation of biodegradable polymers. RSC Adv. 7, 55720– 55724.
- 68. Norikane, Y., Uchida, E., Tanaka, S., Fujiwara, K., Koyama, E., Azumi, R., Akiyama, H., Kihara, H., and Yoshida, M. (2014). Photoinduced crystal-to-liquid phase transitions of azobenzene derivatives and their application in photolithography processes through a solid-liquid patterning. Org. Lett. 16, 5012–5015.
- 69. Suzuki, A., and Tanaka, T. (1990). Phase transition in polymer gels induced by visible light. Nature 346, 345–347.
- Pandey, S.S., Banerjee, N., Xie, Y., and Mastrangelo, C.H. (2018). Self-destructing secured microchips by on-chip triggered energetic and corrosive attacks for transient electronics. Adv. Mater. Technol. 3, 1800044.

- Sim, K., Wang, X., Li, Y., Linghu, C., Gao, Y., Song, J., and Yu, C. (2017). Destructive electronics from electrochemical-mechanically triggered chemical dissolution. J. Micromech. Microeng. 27, 065010.
- Chen, Y., Wang, H., Zhang, Y., Li, R., Chen, C., Zhang, H., Tang, S., Liu, S., Chen, X., Wu, H., et al. (2019). Electrochemically triggered degradation of silicon membranes for smart on-demand transient electronic devices. Nanotechnology 30, 394002.
- Wu, S., Wang, H., Sun, J., Song, F., Wang, Z., Yang, M., Xi, H., Xie, Y., Gao, H., Ma, J., et al. (2016). Dissolvable and biodegradable resistive switching memory based on magnesium oxide. IEEE Electron. Device Lett. 37, 990–993.
- 74. Sun, J., Wang, H., Song, F., Wang, Z., Dang, B., Yang, M., Gao, H., Ma, X., and Hao, Y. (2018). Physically transient threshold switching device based on magnesium oxide for security application. Small 14, 1–7.
- Xu, J., Zhao, X., Wang, Z., Xu, H., Hu, J., Ma, J., and Liu, Y. (2019). Biodegradable natural pectin-based flexible multilevel resistive switching memory for transient electronics. Small 15, 1803970.
- Liu, D., Zhang, S., Cheng, H., Peng, R., and Luo, Z. (2019). Thermally triggered vanishing bulk polyoxymethylene for transient electronics. Sci. Rep. 9, 18107.
- Bae, H., Lee, B.H., Lee, D., Seol, M.L., Kim, D., Han, J.W., Kim, C.K., Jeon, S.B., Ahn, D., Park, S.J., et al. (2016). Physically transient memory on a rapidly dissoluble paper for security application. Sci. Rep. 6, 38324.
- 78. Lee, C.H., Kang, S.K., Salvatore, G.A., Ma, Y., Kim, B.H., Jiang, Y., Kim, J.S., Yan, L., Wie, D.S., Banks, A., et al. (2015). Wireless microfluidic systems for programmed, functional transformation of transient electronic devices. Adv. Funct. Mater. 25, 5100–5106.
- Chang, J.K., Fang, H., Bower, C.A., Song, E., Yu, X., and Rogers, J.A. (2017). Materials and processing approaches for foundrycompatible transient electronics. Proc. Natl. Acad. Sci. U S A 114, E5523–E5529.
- Yoon, J., Lee, J., Choi, B., Lee, D., Kim, D.H., Kim, D.M., Moon, D.I., Lim, M., Kim, S., and Choi, S.J. (2017). Flammable carbon nanotube transistors on a nitrocellulose paper substrate for transient electronics. Nano Res. 10, 87–96.
- Kim, B.H., Kim, J.H., Persano, L., Hwang, S.W., Lee, S., Lee, J., Yu, Y., Kang, Y., Won, S.M., Koo, J., et al. (2017). Dry transient electronic systems by use of materials that sublime. Adv. Funct. Mater. 27, 1606008.
- Gumus, A., Alam, A., Hussain, A.M., Mishra, K., Wicaksono, I., Torres Sevilla, G.A., Shaikh, S.F., Diaz, M., Velling, S., Ghoneim, M.T., et al. (2017). Expandable polymer enabled wirelessly destructible high-performance solid state electronics. Adv. Mater. Technol. 2, 1600264.
- Gao, Y., Sim, K., Yan, X., Jiang, J., Xie, J., and Yu, C. (2017). Thermally triggered mechanically destructive electronics based on electrospun poly(epsilon-caprolactone) nanofibrous polymer films. Sci. Rep. 7, 947.
- 84. Lin, R., Yan, X., Hao, H., Gao, W., and Liu, R. (2019). Introducing temperature-controlled





phase transition elastin-like polypeptides to transient electronics: realization of proactive biotriggered electronics with local transience. ACS Appl. Mater. Interfaces 11, 46490–46496.

- Zhang, X., Weber, C.M., and Bellan, L.M. (2019). Thermoresponsive transient radio frequency antennas: toward triggered wireless transient circuits. Adv. Mater. Technol. 4, 1900528.
- 86. Lee, H., Lee, G., Yun, J., Keum, K., Hong, S.Y., Song, C., Kim, J.W., Lee, J.H., Oh, S.Y., Kim, D.S., et al. (2019). Facile fabrication of a fully biodegradable and stretchable serpentineshaped wire supercapacitor. Chem. Eng. J. 366, 62–71.
- Jiang, W., Li, H., Liu, Z., Li, Z.Z., Tian, J., Shi, B., Zou, Y., Ouyang, H., Zhao, C., Zhao, L., et al. (2018). Fully bioabsorbable natural-materialsbased triboelectric nanogenerators. Adv. Mater. 30, 1801895.
- Yin, L., Huang, X., Xu, H., Zhang, Y., Lam, J., Cheng, J., and Rogers, J.A. (2014). Materials, designs, and operational characteristics for

fully biodegradable primary batteries. Adv. Mater. *26*, 3879–3884.

- Lu, L., Yang, Z., Meacham, K., Cvetkovic, C., Corbin, E.A., Vázquez-Guardado, A., Xue, M., Yin, L., Boroumand, J., Pakeltis, G., et al. (2018). Biodegradable monocrystalline silicon photovoltaic microcells as power supplies for transient biomedical implants. Adv. Energy Mater. 8, 1703035.
- Lei, T., Guan, M., Liu, J., Lin, H.C., Pfattner, R., Shaw, L., McGuire, A.F., Huang, T.C., Shao, L., Cheng, K.T., et al. (2017). Biocompatible and totally disintegrable semiconducting polymer for ultratin and ultralightweight transient electronics. Proc. Natl. Acad. Sci. U S A 114, 5107–5112.
- Kim, D.-H.H., Viventi, J., Amsden, J.J., Xiao, J., Vigeland, L., Kim, Y.-S.S., Blanco, J.A., Panilaitis, B., Frechette, E.S., Contreras, D., et al. (2010). Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics. Nat. Mater. 9, 511–517.
- 92. Hosseini, N.R., and Lee, J.S. (2015). Biocompatible and flexible chitosan-based

resistive switching memory with magnesium electrodes. Adv. Funct. Mater. 25, 5586–5592.

Matter Review

- Choi, Y.S., Koo, J., Lee, Y.J., Lee, G., Avila, R., Ying, H., Reeder, J., Hambitzer, L., Im, K., Kim, J., et al. (2020). Biodegradable polyanhydrides as encapsulation layers for transient electronics. Adv. Funct. Mater. 30, 2000941.
- 94. Raman, R., Hua, T., Gwynne, D., Collins, J., Tamang, S., Zhou, J., Esfandiary, T., Soares, V., Pajovic, S., Hayward, A., et al. (2020). Lightdegradable hydrogels as dynamic triggers for gastrointestinal applications. Sci. Adv. 6, eaay0065.
- **95.** Meng, H., and Li, G. (2013). A review of stimuliresponsive shape memory polymer composites. Polymer (Guildf) 54, 2199–2221.
- Balk, M., Behl, M., Wischke, C., Zotzmann, J., and Lendlein, A. (2016). Recent advances in degradable lactide-based shape-memory polymers. Adv. Drug Deliv. Rev. 107, 136–152.
- Li, Z., Song, N., and Yang, Y.W. (2019). Stimuliresponsive drug-delivery systems based on supramolecular nanovalves. Matter 1, 345–368.