Development and application of transient electronic based on degradable materials

Wei Wei, Xianghong Ren*, Siyan Du and Feng Zhou
High-Tech Institute of Xi’an, Xi’an, China

*Corresponding author e-mail: renxh701@163.com

Abstract. Using degradable metals and metal oxides as electrodes or interconnecting wires, Si and SiO₂ as semiconductor or dielectric layers, and degradable materials as base films or encapsulation protective layers, the physical form of transient electronic devices is partially damaged or completely disappeared by the corresponding degradation mode triggered by external stimuli, after performing specified functions or discarding them. This paper combs the practical needs of transient electronic in environmental protection, health care, information security, etc. and comprehensively analyzes the proposed process of transient electronic concepts. The current research status and development trend of Transient Electronics are discussed from three aspects: biocompatibility, full material degradation and controllable degradation. In the end, the article looks forward to the future development and application prospects of transient electronic.

1. Introduction
Transient Electronics technology led by biodegradable film and nano-scale electronic printing has subverted people’s understanding of electronic devices and has great potential in environmental protection, health care, and information security. In 2016, Academician Huang Wei of the Chinese Academy of Sciences expressed in the “High-end Forum on Cross-innovation of Materials Science and Information Science” that flexible electronic technology will drive the market of RMB 1 trillion, help traditional industries increase industrial added value, and bring revolutionary changes to industrial structure and human life [1]. The wide application of electronic products in communication, office, production, entertainment, medical care, etc., has a tremendous impact on human society. The larger negative impact is the large amount of electronic waste. E-wastes containing a large amount of heavy metal elements and stable polymers containing fluorine, chlorine, sulfur and other refractory polymers, even if they are treated by conventional methods such as crushing, landfilling, and incineration, cause serious pollution to water, land and air. Transient Electronic technology, based on the development of biodegradable, renewable, zero-emission, low-toxic electronic devices, is expected to reduce 50 million tons of e-waste each year through biodegradation and recycling [2]. Medical implants and electronic products with good biodegradability and biocompatibility, are used as surgical sutures, tissue engineering scaffolds, hemostatic agents, drug release vehicles, auxiliary diagnosis and treatment [3], etc. It can reduce the rejection reaction between medical materials and human body, and avoid secondary pain and side effects caused by suture or auxiliary material removal surgery. Transient
Electronics can be controlled to decompose and spread to the surrounding environment when not in use, thereby protecting the information stored in the device.

2. The concept of transient electronic

Transient Electronics, first proposed by the University of Illinois at Urbana-Champaign, Tufts University, and Northwestern University’s John Rogers and colleagues, is called “transient electronic technology”, as a method of producing biodegradable electronic devices and medical implants [4].

In 2012, Hwang S W, Tao H, et al. reported a physically transient form of silicon electronics in science [5]. Using Mg as electrode material, MgO as interlayer dielectric material, Si and SiO₂ as semiconductor doping materials, basic components such as transistors, diodes, inductors, capacitors and resistors are fabricated, and sensors, drivers, power systems and wireless control strategies are used. The functional design system is integrated with the silk fibroin film substrate to form an implantable transient device. The device is biodegradable and can be rapidly dissolved in deionized water and phosphate buffer. The subcutaneous tissue implanted in the dorsal side of the mouse for 15 days is mostly dissolved and completely degraded and absorbed for 3 weeks. The experiment constructed a system-wide Transient Electronics application model to verify the device’s good biocompatibility, degradability and application value in implantable medicine.

![Figure 1](https://example.com/f1)

**Figure 1.** (a) (b) An integrated electronic device composed of electronic components prepared from materials such as silicon, magnesia, magnesium, etc., and a schematic diagram thereof. (c) a process in which the device rapidly degrades in water [5].

Transient electronic device refers to an emerging electronic device whose physical form can partially disappear or disappear completely under the trigger of external stimulus after the specified function is completed [2]. Transient electronic devices mainly include degradable polymer substrates/encapsulation materials, transient interconnect wires, and functional components composed of semiconductors [6]. The key feature is that under the trigger of external stimuli, it may be water, oxygen, PH, temperature, ultraviolet light, etc., the controllable function fails under the command, and then rapidly degrades in the environment that some of the physics disappears or disappears completely. The materials that can be used as transient electronic mainly include silicon, metal oxides, natural polymer materials, and high molecular polymers. Among them, silicon and silicon dioxide are often used as dielectric layers or semiconductors, and metal oxides include Mg, MgO, and Zn, ZnO and the like are used as electrodes or interconnecting wires, natural polymer materials such as silk fibroin, paraffin, chitosan, gelatin, etc., and high molecular polymers including polyvinyl alcohol (PVA), polylactic acid (PLA), polycaprolactone (PCL) or the like is often used as a substrate or packaging material because of its good film formability and degradability.
3. Research status and development trend of transient electronic

In 2015, Kun Kelvin Fu et al. outlined the latest advances in transient electronic from metal, polymer and semiconductor materials and transient electronic design and development [7], and proposed that current transient electrons are mainly used in implantable medical, battery, Research on FETs, energy storage devices, and the preparation of simple functional circuits. From the perspective of transient electronics research in recent years, the next development trend mainly includes the following three aspects: ensuring biocompatibility for implantable medical treatment; preparing typical components based on full material degradation; exploring controlled degradation, Design function transient.

Figure 2. Transient electronic materials and devices [7]

3.1. Ensure biocompatibility for implantable medical treatment

The initial concept and research direction of transient electronic is directed to implantable medicine. Regardless of the development of technology, it is applied to a wider range of fields, but medical implants have always been an important use. Transient electronics for implantable medical applications require both complete degradation and good biocompatibility in substrate selection. In 2015, Sung Hun Jin et al. reported on amorphous indium-gallium-zinc-oxide (a-IGZO) based transistors and circuits in ACS applied materials and interfaces [8]. The demonstration circuit is firstly formed by forming a nickel film on a silicon wafer, then using SiO2 and Mo as the gate, SiN and SiO2 as the gate dielectric, and a-IGZO as the active material, taking electron beam evaporation and light. The functional device was prepared by engraving and acetone extraction, and finally transferred to the PVA base film to form a-IGZO thin film transistors (TFTs) and circuits. Transient devices, at 19 volts supply voltage, ohmic contact characteristics and 5.67 kHz oscillating frequencies are comparable to similar devices. At the same time, all materials used for device preparation are water-soluble. The fabricated a-IGZO TFTs and circuits can be rapidly degraded in DI and PBS at 60°C and bovine serum at 37°C. The device partially dissolves after 600 seconds in DI and contains after 1800 seconds. The PVA substrate is completely dissolved in the internal device. Transient degradability and biocompatibility of a-IGZO TFTs and circuits provides data reference and application exploration for implanted medical applications.

In 2018, Ki Yoon Kwon et al. Reported transient electronic based on biocompatibility and degradable fructans on Small [9]. Using Mg as conductor and electrode, SiO2 as interlayer dielectric to prepare metal oxide semiconductor array, transfer on fructan substrate and Si nano film substrate to form an n-channel metal—oxide—semiconductor (NMOS) Array. The system life cycle is programmed according to the animal model, and the selective control of the trigger dissolution can be realized. The experimentally tested transient electronic device can be completely degraded in DI for 45 minutes, and there is no adverse reaction in the subcutaneous tissue implanted in the mouse, and partially degraded after 5 days. It is completely absorbed after 20 days.
3.2. Preparation of typical components based on full material degradation

With the wide application and service of electronic products in our production and life, people have caused great troubles due to the damage of electronic components, the environmental pollution caused by disposal and the loss of information. The development of typical transient electronic components with full material degradation capability is not only the only way to expand the application of transient electronic technology to deeper levels, but also the practical need to effectively solve the problem of electronic waste. In 2013, Canan Dagdeviren et al. reported on ZnO-based transistors and energy harvester arrays on Small [10]. All TFTs and MEHs are fabricated using Mg as the electrode or interconnect, MgO as the gate or interlayer dielectric, ZnO as the semiconductor or piezoelectric component, and silk fibroin as the substrate or encapsulation material, through polyimide (PI) mask is formed by electron beam evaporation deposition and can be completely dissolved in deionized water for about 60 minutes. At the same time, the degradation of the device is affected by the encapsulation layer and Mg. The degradation time of the device can be controlled by designing the packaging process, the packaging method, and the size and thickness of the materials selected for each structural layer.
Luo Li and Zhang Chunfu of Xidian University of Technology discussed the research of flexible organic solar cells based on physical transient substrates [11]. The Ag film on the substrate is used as the anode, MoO$_3$ is used as the anode buffer layer, P3HT: PCBM is used as the optical effective layer, and Ca/Ag is used as the cathode of the battery to prepare a flexible organic solar cell. The specific structure is PVA-based substrate/Ag/MoO$_3$/P3HT: PCBM/Ca/Ag. The physical transient characteristics of solar cell devices with pure PVA, PVA/gelatin and PVA/sucrose were studied. The PVA/sucrose-based battery has the fastest degradation rate, the best light transmission and the highest efficiency. When the ratio of PVA to sucrose is 2:1, the substrate film has a light transmittance of up to 90%, which can be compared with glass, and the energy conversion efficiency is up to 1.88%, the device which can be fully damaged in 20 seconds.

Figure 5. (a) Schematic diagram of TFTs and MEHs consisting entirely of water-soluble materials. (b) Image of a set of TFTS and MEHS on silk substrates. (c) Soaking process of TFTs and MEHs in deionized water at room temperature [10].

Figure 6. Dissolution process of organic solar cells with PVA/sucrose substrate in deionized water at room temperature [11].
In 2018, Xu Jiaqi and Zhao Xiaoning of the Northeast Normal University reported on the small biodegradable natural pectin-based flexible multi-stage resistive switch memory [12]. The prepared Ag/pectin/indium tin oxide (ITO) multi-stage resistive switching memory has a significant RS characteristic memory device with low operating voltage (≈1.1V), fast switching speed (<70ns), and long retention time (>10s) and strong bending performance (>10 times). Pectin extracted from natural orange is used as a base material. Due to the presence of hydrophilic groups, especially carboxyl groups, in pectin, pectin has good water solubility and biocompatibility, and can be completely deionized in 10 minutes. Dissolved. The study provides a systematic application for the storage of confidential information, demonstrating the potential value of natural pectin as a transient electronic substrate material.

\[ \text{Figure 7. Dissolution process of Ag/pectin/ITO storage in deionized water at room temperature [12].} \]

3.3. Exploring Controlled Degradation, Designing Functional transient electronic

In the specific application practice, we always hope that the electronic products can run stably during the mission time, and at the same time, they can be reliably degraded after completing the task, so as to avoid leakage of the carried information. This puts higher requirements for controllable degradation of transient electronics at the design level. It is necessary to introduce a triggering program for degradation initiation in the circuit, which can effectively control the timing and rate of degradation. In 2016, Katherine L. Camera et al. reported the transient properties of thermosensitive polycarbonate and its composites on Polymer [13]. The thermal and mechanical properties of vaporizable polycarbonate (VPC) and its composites were analyzed and blended to prepare heat sensitive materials that meet the needs of different applications. Both evaporable polycarbonate and its commercial polycarbonates have an acid-sensitive group that, when combined with an acid source, can be catalytically decomposed in a few minutes to achieve a decomposition temperature between 160°C and 250°C. By controlling the blending ratio, the Young’s modulus of these nanocomposites can be adjusted from 4 MPa to 2 GPa. Thermal polycarbonate and its composites, with low thermal decomposition temperature and good mechanical properties, can be quickly and thoroughly degraded under thermal triggering conditions and can be used as effective transient substrate materials.
In 2017, Fang Xu et al. reported on the controllable degradable transient electronic antenna based on water-soluble PVA/TiO₂ film on Electronic materials [14]. The coplanar waveguide (CPW)-type transient antenna on the PVA/TiO₂ substrate film was controlled by magnetron sputtering. The dielectric properties and dissolution rate of the composite film were adjusted by controlling the addition of titanium dioxide nanoparticles. When the PVA:TiO₂ mass ratio is 100:1, the dielectric constant and dielectric loss reach 3.23 and 0.038 at 1.0 GHz, respectively, and the antenna can be physically degraded in DI for 45 min. The design and manufacturing methods described in this paper can be used as reference and reference for other transient devices with complex structures and functions.

Figure 9. Dissolution of the antenna in deionized water at a mass ratio of PVA to TiO₂ of 100:1 under ambient conditions [14].
In 2017, Gerald Gourdin et al. reported on photo-triggered full-transient electronics at the 67th IEEE Electronic Components and Technology Conference: component and device fabrication [15]. The demonstration circuit uses a polyphthalate film as a substrate, an acid-sensitive metastable polymer is incorporated into a photo-acid generator (PAG) as an interlayer medium, and a phthalaldehyde (PHA) is used to fill the nanometer. Silver and degradable metal materials are electrically conductively wired, and components and circuits are prepared by screen printing and multilayer printing. By controlling the concentration of PAG and the intensity of light irradiation, the degradation rate of the device can be adjusted, and each component has good elastic modulus, electrical resistivity and connectivity, providing a light-triggered and controllable transient electronic design.

Figure 10. (a) Complete multilayer demonstration circuit. (b) Partial depolymerization details of surface and internal printed wiring [15].

4. Conclusion
Transient electronic technology has received extensive attention for its potential applications in the fields of environmental protection, biomedical, information security, and military equipment. Although it has been proposed for only a few years, it is in the process of degradable materials, substrates and circuits. Great progress has been made in the design and preparation of functional components. However, we must also see that transient electronic are still in the initial stage of development. In addition to application in implantable medicine, applications in other fields are still mainly at the level of exploration and research, and there is still a big contradiction with the actual needs of current social production and life. There is still a big gap in the production of large-scale commercial transient electronic devices. Compared with traditional electronic products, there are mainly the following problems: First, transient electrons have flexibility and degradability, and there are still difficulties in continuous and stable operation in complex environments. Second, transient electronic preparation and processing processes require high levels. There are still difficulties in production; the third is that transient electrons are relatively high in the production of green and environmentally friendly materials, and the production cost is relatively high. There are still difficulties in marketing and substitution. Fourth, there are many factors affecting transient electronic degradation. There are difficulties in the timing and progress of degradation.

The development of the next step transient electrons should focus on the following aspects: First, continue to explore the degradable materials, and explore the superior lining in terms of film formation, biocompatibility, environmental adaptability and mechanical properties. The bottom material; the second is to continue research and development in the processing technology, to develop processing conditions that are easier to implement and cheaper to manufacture. The third is to continuously optimize the device design, strengthen the overall design and system integration, and prepare transient functional devices with precise controllable degradation time, degradation mode, and degradation rate and
degradation degree. As materials, processes, devices, etc. mature further, the use of transient electronic parts to replace traditional electronic products in various fields of production and life can be expected in the future.

References

[1] Huang Wei. Flexible electronic technology will drive the market of trillions of dollars. Hangzhou Chemical [J]. 2016, 46 (04): 18.

[2] Xu Hang, Huang Xian. 2017 Transient Electronic Technology Hotspot Review. Science and Technology Herald [J]. 2018, 36 (01): 12-17.

[3] Chen Gui, Yang Libao. Biodegradable materials and their applications in biomedicine. New materials industry [J]. 2018, 12, (09): 38-41.

[4] Gao Lingyun. Biodegradable Circuit. Keyyuan News [J]. 2013, 25 (03): 55.

[5] Hwang S W, Tao H, Kim D H, et al. A Physically Transient Form of Silicon Electronics. Science [J]. 2012, 337: 1640–1644

[6] Zhang Ying, Lu Bingwei, Xu Hangxun, et al. Recent advances in transient electronic devices research. China Science [J]. 2016, 46 (04): 044605

[7] Kun Kelvin Fu, Zhengyang Wang, et al. Transient Electronics: Materials and Devices. Chemistry of Materials [J]. 2015, 5b04931

[8] Jin S. H., Kang S., Cho I., et al. Water-soluble thin film transistors and circuits based on amorphous indium-gallium-zinc oxide. ACS applied materials & interfaces [J]. 2015, 7 (15): 8268-8274.

[9] Ki Yoon Kwon, Ju Seung Lee, et al. Biosafe, Eco-Friendly Levan Polysaccharide toward Transient Electronics. Small [J]. 2018, 180: 13-32.

[10] Dagdeviren C., Hwang S., Su Y., et al. Transient, Biocompatible Electronics and Energy Harvesters Based on ZnO. Small [J]. 2013, 9 (20): 3398-3404.

[11] Luo Li. Research on Flexible Organic Solar Cell Based on Physical Transient Base. Xi’an University of Electronic Science and Technology [M]. 2015: 21-44.

[12] Xu J., Zhao X., Wang Z., et al. Biodegradable Natural Pectin-Based Flexible Multilevel Resistive Switching Memory for Transient Electronics. Small [J]. 2019, 15 (4): 1803970.

[13] Katherine L. Camera, Brandon Wenning, et al. Transient materials from thermally-sensitive polycarbonates and polycarbonate nanocomposites. Polymer [J]. 2016, 101: 59-66.

[14] Xu F., Zhang H., Jin L., et al. Controllably degradable transient electronic antennas based on water-soluble PVA/TiO2 films. Journal of Materials Science [J]. 2018, 53 (4): 2638-2647.

[15] Gerald Gourdin, Oluwadamilola Phillips, et al. Phototriggerable, Fully Transient Electronics: Component and Device Fabrication. 2017 IEEE 67th Electronic Components and Technology Conference [C]. 2017:129: 190-196.