Research review about the progress of transient electronics in sensor and electronic skin

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Abstract. Transient electronics, a new type of electronic device, is made of degradable materials. After a programmed set period of operations, transient electronics can be partially or completely degraded when they are subjected to certain stimulus. Transient electronics can work normally without extreme conditions, and can degrade immediately after stable operation. It could supplement the limitation of traditional electronics, and could be of great interest for applications in electronic skin and sensors.

1. Introduction
At present, with the rapid change of electronic devices[1], more and more discarded devices pose a great threat to the ecological environment[2,3]. Therefore, it is a general trend to use degradable materials to manufacture electronic devices. In addition, as for medical care, applying the materials featuring biocompatibility and degradability to operation is helpful to prevent a secondary operation[4], thus the patients’ pain and medical cost will be reduced greatly[5]. Therefore, based on biodegradable materials, combined with the latest microelectronic device machining technology, the preparation of degradable transient electronics has become the mainstream research direction.

Transient electronic device is a kind of electronic device which is made of biodegradable materials and can dissolve in part or as a whole at a controlled speed after its stable operation. Compared with the long-term stable operation of the traditional device, this kind of electronics with “transient” characteristics not only carries the conventional performance of ordinary devices, but can physically and functionally disappear when they are subjected to external stimulation or relevant instructions. Therefore, transient electronics has an excellent prospect in electronic skin and sensors (Fig. 1). In this paper, we summarize the research progress of transient electronics in sensor and electronic skin in recent years.
2. Sensor

Based on transient electronic technology, the sensor devices not only have various functions of common sensors, but can realize self degradation after the operation. Bao Zhenan’s team\(^6\) has developed a sensor for blood flow, and its fabrication procedure is based on biodegradable materials. After applying it in the experiments of human artery models and rats, they found that the sensor can achieve biocompatibility and pulse detection. Due to its biodegradable properties, the sensor will be absorbed in a few months without dismantling the equipment. The sensor is expected to show a variety of applications in medical surgery. Degradable materials play fundamental roles in the operation of transient electronics. Wang Lili’s team\(^7\) has reported a degradable flexible humidity sensor based on Natural Chitosan or lignin composite bio-materials and Zhang Afang’s research group\(^8\) prepared degradable thermoresponsive cyclodextrin-based polyrotaxanes by using alkoxy etherified cyclodextrin derivatives as the building units. These materials can be integrated in such fields as drug delivery, wearable flexible electronic devices and intelligent bio-materials.

Cellulose is a natural polymer and one of the sources of biodegradable materials. In the research on cellulose-based materials made by Yu Haipeng’s team\(^9\), it is shown that flexible circuits and sensors can be well prepared by converting cellulose materials into electronic conductive materials through carbonization. The team of professor Jeffrey M. Mativetsky\(^10\) has prepared a new mechanical sensor based on natural cellulose. After more than 3000 pressure cycling tests, its response time is 20ms, and the current change is only reduced by 4.6%, and it can also achieve rapid degradation. Thus, this device can be well used in medical diagnosis. Chang Yu’s team\(^11\) once proposed the ionization sensing paper, which is regarded as an integrated flexible sensing platform. This device shows a potential application prospect in health wearability.

In addition to cellulose, hydrogel is also one of the important components of degradable materials. Tao Hu’s research group\(^12\) has developed a flexible mechanical sensor. This sensor takes silk protein hydrogel as the substrate. By adjusting the temperature sensitive papain and the gold nanoparticles with photoinduced heating effect, the temperature of the flexible mechanical sensor could be changed (or degraded by using laser). Therefore, the multi-function of controllable degradation rate could be achieved. Guo Baolin’s research team\(^13\) has also studied hydrogels. They have proposed a self-repairing nanocomposite hydrogel, subsequently, the conductive antioxidant gel is prepared by mixing up biocompatible polymer N-carboxyethyl chitosan and oxidized hyaluronic acid grafted aniline tetramer polymer. After that, professor Bao Zhenan’s team\(^15\) by transferring the ionic gels to design a new type of hydrogel conductor material system. These materials have broad application prospects in wound healing and other medical systems. The preparation of transient electronic devices with super performance depends not only on the degrad
ability of the material, but also on the preparation method. Zhang Yuanjian’s research group\cite{16} has prepared photoelectrochemical biosensors through mechanical grinding method\cite{17}. Subsequently, the research group prepared carbon nitride nanoparticles through\cite{18} nano precipitation method with poor solvent. After applying the prepared carbon nitride nanoparticles to the photocatalytic degradation of dyes, their performance is 2.5 times higher than the original one. This method provides a new idea for batch preparation of nanostructured carbon nitride.

Researchers from the University of Connecticut have developed\cite{19} a biodegradable sensitive sensor. The sensor was prepared by spinning biodegradable polymer polylactic acid into nanofiber and using it as the substrate. The experiment of mice proves that the sensor is biodegradable. In addition, the device could generate well controlled ultrasound to help the drugs be injected into the blood enter the brain tissue. Li Baojun’s team has studied\cite{20} a biosensor with biocompatibility, which realizes real-time detection of blood diseases and targeted transportation of micro particles. Furthermore, there are organic biosensors\cite{21}, enzyme biosensors and DNA biosensors. John’s team has designed\cite{22} and developed two kinds of bioabsorbable optical pressure sensors (FPI and PC structures). The sensor uses the temperature dependent refractive index of silicon materials to detect the intracranial temperature. These technologies provide a biocompatible tool for early diagnosis and drug delivery of blood diseases.

3. Electronic Skin

Transient electronics is also widely used in electronic skin. Academician Wang Zhonglin’s team has developed an electronic skin\cite{23}. The skin is made by sandwiching silver nanowires between polylactic acid glycolic acid and polyvinyl alcohol. The antibacterial and biodegradation rate of the electronic skin are changed by adjusting the concentration of silver nanowires and the selection of polyvinyl alcohol and polylactic acid-glycolic acid. The electronic skin can monitor the physiological signal and joint movement of the whole body in real time. And this study provides a new strategy for the development of multifunctional electronic skin. Cellulose are rich in resources, environmental friendly and biodegradation, which help Sui Xiaofeng’s team develop\cite{24} a cellulose porous material. Yu Haidong’s team has developed\cite{25} a kind of transparent fish glue film, which is made of fish scales. Experiments show that these films can be dissolved in water in a few seconds at 60°C, and can be completely degraded in soil within 24 days. Yin Lan’s team\cite{26} has prepared a flexible degradable substrate material of poly (lactic acid) and poly (trimethylene carbonate) by template method. The experiments show that the whole device can completely disappear and degrade in physiological environment. There are some methods for obtaining electronic skin materials, in addition these methods are gradually improving.

At the same time, in terms of preparation technology, researchers are constantly exploring. Based on the strong interaction between silk fibroin (SF) and polyurethane, Liu Xiangyang’s team\cite{27} has synthesized a solid and heat-resistant silk fibroin composite film by mesoscopic doping of SF, and acquired flexible circuit integrated electronic skin by ink-jet printing. Leng Jingsong’s team\cite{28} has proposed a biodegradable and remote controlled shape memory polymer occluder combined with 4D printing technology. Moreover, Huang Xian once proposed that the transient ink could be prepared by ball milling method\cite{29}, and then the transient device could be processed by electronic printing technology combined with light sintering. However, due to the limited choice of raw materials for transient conductive ink, the processing of transient electronics is time-consuming and laborious. Then they put forward the concept of self sintering with anhydride assistance at room temperature\cite{30}. Then developed a new nano metal conductive ink based on nano zinc and anhydride, and the corresponding new sintering method. It is the first time to realize the transient sintering of ink circuit by steam at room temperature. The series of methods they put forward are of great significance to the development of transient electronics, especially for applications in the field of electronic skin.

Bao Zhenan\cite{31-33}, the “mother of electronic skin”, has made some achievements\cite{34,35} since he began to study electronic skin in 2008. This team reported\cite{36} a biocompatible and completely decomposable semiconductor polymer in 2017, and applied it to ultra-thin and ultra-light transient electronic devices. Its components can be easily decomposed under mild acidic conditions. Subsequently, the research
team[37] developed a preparation process that can achieve high yield and uniform device performance for different intrinsic stretchable materials, therefore, the team studied multi-component electronic skin[40], which can be self-healing and stretchable in 2018.

4. Conclusion
The biggest advantage of transient electronic device is that it can be partially or completely degraded under external stimulation after a programmed set period of operation. This kind of electronic device is comparable to the traditional electronics in performance while expand the functions. In recent years, the researches of transient electronics in biodegradable materials, device preparation process and transient functional devices have made some progress, which also play a certain role in promoting the development of transient electronics. And transient electronic technology could be integrated in biomedical devices, electronic safety devices and environmental sensors.

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