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Review

Recent development of transient electronics

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HIGHLIGHTS

- A number of inorganic materials and their method of application were studied.
- Models of reactive diffusion were presented to predict the dissolution behavior.
- Various encapsulation approaches were explored as a way to extend the lifetime.
- The transient ECG sensor was configured in a stretchable layout.

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ABSTRACT

Transient electronics are an emerging class of electronics with the unique characteristic to completely dissolve within a programmed period of time. Since no harmful byproducts are released, these electronics can be used in the human body as a diagnostic tool, for instance, or they can be used as environmentally friendly alternatives to existing electronics which disintegrate when exposed to water. Thus, the most crucial aspect of transient electronics is their ability to disintegrate in a practical manner and a review of the literature on this topic is essential for understanding the current capabilities of transient electronics and areas of future research. In the past, only partial dissolution of transient electronics was possible, however, total dissolution has been achieved with a recent discovery that silicon nanomembrane undergoes hydrolysis. The use of single- and multi-layered structures has also been explored as a way to extend the lifetime of the electronics. Analytical models have been developed to study the dissolution of various functional materials as well as the devices constructed from this set of functional materials and these models prove to be useful in the design of the transient electronics.

Contents

1. Introduction

While the development of modern electronics has typically been concerned with durable devices that function stably over time, the advent of transient electronics takes an opposite approach; the destruction of the said devices is designed to provide unique opportunities. Upon exposure to water, transient electronics disintegrate at a predictable rate while releasing biologically and/or environmentally benign end products [1,2]. This ability opens a wide range of applications from bio-degradable electronics to diagnostic/therapeutic implants [3,4]. One can use an electronic component, for instance, as a temporary implant in a patient and allow it to safely dissolve on its own without the need for a second surgery [1,5]. Ultimately, transient electronics can solve the problem of disposing electronics in a safe and convenient manner [6–8].

The defining quality of transient electronics is their ability to dissolve into non-toxic products upon exposure to water and,

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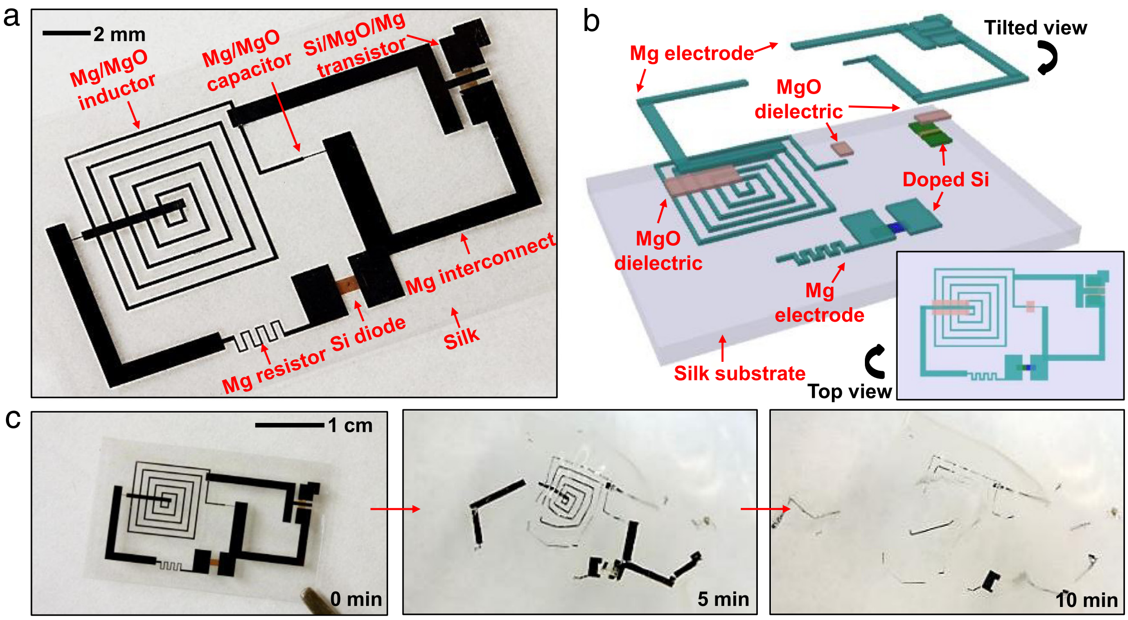

Fig. 1. Proof-of-concept demonstration for transient electronics, with key materials and device structure layout. (a) Image of a device with all components deployed on a thin silk substrate. The device components include transistors, diodes, inductors, capacitors, and resistors, with interconnects and interlayer dielectrics. (b) Schematic illustration in an exploded view, with a top view in the lower right inset. (c) Images showing the time sequence at various dissolution stages in deionized (DI) water. *Source:* Reprinted with permission from Ref. [1].

naturally, dissolution accounts for a significant amount of research in this field [1,2,9–12]. Early research on this topic resulted in achieving the partial dissolution of components through the use of organic materials as substrates [13,14]. For instance, organic thin-film transistors have been developed using cotton-made paper [15] as substrate and silk was also shown to be useful as a soluble substrate for implants in the body [16]. However, this type of research was limited to the substrate and the electronic devices remained insoluble.

More recently however, electronics which are completely soluble have been developed. This relies on a recent, important discovery that semiconductor grade monocrystalline silicon can undergo dissolution in bio-fluids or even water at physiological conditions with a programmed lifetime relevant to applications in biomedicine [1]. As the reaction rate of silicon hydrolysis to form silicic acid ($Si(OH)_4$) is exceptionally small, silicon devices were fabricated in extremely thin forms. A nanomembrane of silicon with lateral dimensions similar to conventional circuits but with a thickness of 70 nm has been shown to dissolve in ~10 days [1]. Via similar chemistry, thin silicon dioxide (SiO_2) was selected as a gate dielectric. Taken together with the other dissolvable, inorganic materials such as magnesium (Mg) and magnesium oxide (MgO) for conductors and the interlayer dielectric, respectively, due to their spontaneous reaction with water to form biologically benign $Mg(OH)_2$, silicon nanomembranes provide a basic means for the construction of a transient, electronic device. As a proof-of-concept, Fig. 1(a) and (b) present a schematic demonstration platform which utilizes silicon nanomembranes (Si NMs) for the semiconductors, magnesium for the conductors, magnesium oxide and silicon dioxide for the dielectrics, and silk for the substrate and packaging materials. The collectively configured devices dissolve and disintegrate when immersed in DI water (Fig. 1(c)).

Surface reactions typically dominate the dissolution behavior for sufficiently large reaction constants. The porosity of the materials (e.g., Mg, MgO and SiO_2) however, was found to be influential as it allows for the diffusion of water through the material, thereby increasing the dissolution rate through an increase in the effective surface area [12]. In studying the dissolution of transient electronics, the factors to consider include physical and chemical properties of materials, and certain ambient factors of an aqueous environment. Given the research of these factors and others, analytical models have been developed to solidify the understanding of the dissolution behaviors in transient electronics [1,11,12]. Such models can be of great assistance in the design of transient electronics. This review will first provide a comprehensive discussion on the hydrolysis of semiconducting materials with a focus on silicon nanomembranes, followed by the model of reactive diffusion to account for the dissolution behavior of porous materials. When combined with ideas from soft, tissue-like electronic devices, the class of transient electronics provides a viable means to monitor health or deliver care in a minimally obtrusive way.

2. Hydrolysis of semiconducting materials

To establish a realistic set of functional materials, knowledge regarding the chemical kinetics of each material is critical, especially that of the hydrolysis of semiconducting materials. At physiological pH levels and temperatures, the dissolution rates of semiconducting materials (e.g., silicon, silicon–germanium, and germanium) are remarkably small [17]. Therefore, in order to minimize the amount of semiconducting materials which must be dissolved, the nanomembrane structure is critical. Dissolution of monocrystalline silicon nanomembranes in phosphate buffered saline (PBS with pH = 7.4) at biologically pertinent temperatures (e.g., 37 °C) forms either an intermediate oxidation product SiO_2 or $Si(OH)_4$ through the equilibrium: $Si + 4H_2O \leftrightarrow Si(OH)_4 + 2H_2$ [18,19]. The rate depends on the crystal structure, morphology, and doping concentration of silicon [20,21], as well as the temperature and composition of solutions [2,19].

Systematic characterization of the dissolution kinetics for silicon used various bio-fluids at multiple pH levels and temperatures. Patterned Si NMs ($3\ \mu m \times 3\ \mu m \times 70$ nm) were first created on a layer of thermal oxide on a silicon wafer, followed by immersion in aqueous buffer solutions (50 mL, in a petri dish with diameter of 7 cm). The dissolution rate of thermal oxide is negligible in comparison to that of silicon. Thicknesses of Si NMs were measured at a specific time (e.g., every other day) after which the sample was