Glucose-based resistive random access memory for transient electronics

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ABSTRACT
In this research, glucose was adopted as the switching layer of resistive random access memory (RRAM) for transient electronics. The fabricated glucose-based RRAM showed bipolar switching behavior with stable endurance (100 cycles) and retention (10^4 seconds) characteristics, without significant degradation, demonstrating its stable data storage capability and reliability. To investigate the switching mechanism of the glucose-based RRAM, various organic materials were prepared for the switching layer of RRAM. In addition, the dissolution characteristic of the glucose-based RRAM was evaluated to investigate the feasibility of its utilization for transient electronics, using a water-soluble substrate: a sodium carboxymethyl cellulose film. With this approach, a biocompatible glucose-based RRAM was successfully fabricated for future transient electronics.

1. Introduction

Wearable and implantable electronics have attracted considerable interest of late for satisfying humans’ desire for a healthy and safe life. In this regard, various types of wearable electronics, such as smart glasses, smartwatches, and smart bands, have already been commercialized. Moreover, many researches have been conducted to overcome the limits of the present form factor of wearable electronics, and to develop transient electronics that can be made to physically or chemically disappear, or that can be reabsorbed by the human body after providing certain functions [1–4]. The current transient components for their medical applications, however, are predominantly passive components rather than active components. This is because most of the active components (e.g. sensors, transistors, diodes, and optoelectronic devices) for processing bio-signals and data are fabricated through a complex manufacturing process using inorganic-based materials like semiconductors, metals, and insulators [5,6]. Thus, there are still limitations in the application of wearable electronic devices, although inorganic materials have biocompatible properties due to their brittle characteristics [5]. Thus, many researchers are focusing on transient electronics using biocompatible organic materials to overcome the aforementioned issues [7–9]. Furthermore, the concept of system on panel (SOP), which consists of various sensors, drivers, memories, etc. with a display panel, is a well-known technology that has been extensively studied in the display field. Especially, the non-volatile memory devices embedded in the pixels of display panels can dramatically reduce the power consumption and enable a variety of functions as there is no need to operate a column line with a large load capacitance [10–12]. Therefore, resistive random access memory (RRAM) is one of the most interesting non-volatile memory candidates for integration in the display panel, due to its simple device structure (metal–insulator–metal), fast switching speed, and high scalability. In addition, RRAM based on flexible and biocompatible organic materials can be easily applied to next-generation flexible and transient display applications. Thus, an organic-based transient RRAM device with a biocompatible characteristic and that uses a glucose film as the switching layer of the RRAM was suggested. The resistive switching characteristics and reliability of the glucose-based RRAM were investigated through electrical parameter analysis. The switching mechanism was also analyzed using the various organic materials that are used for the switching layer of RRAM, to confirm the detailed switching mechanism. Lastly, glucose-based RRAM on a dissolvable substrate consisting of a sodium carboxymethyl cellulose film was fabricated to verify its feasibility for future transient electronics.

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2. Experiment

2.1. Fabrication process of glucose-based RRAM

Glucose-based RRAM was fabricated through the following process. First, heavily doped \( p \)-type silicon substrates were cut into \( 2 \times 2 \) cm pieces and cleaned via sonication sequentially in acetone, methanol, and deionized (DI) water for 10 minutes each. Second, a glucose film was deposited on a cleaned silicon substrate using the spin coating method, at room temperature. A 0.5 M glucose solution was synthesized by dissolving \( \alpha \)-D-glucose powder (Sigma-Aldrich) in DI water as shown in Figure 1(a). After the deposition of the glucose film, it was annealed at 30°C for 2 hours in ambient air, and then dried in a vacuum state under \( 10^{-3} \) mTorr for 6 hours. Finally, a 120-nm-thick and 600-μm²-square-feature-sized Al top electrode was deposited using a thermal evaporator via a shadow mask. The overall fabrication process of the glucose-based RRAM is shown in Figure 1(b).

2.2. Measurements and analysis method

The electrical characteristics of the RRAM devices were tested under an ambient atmosphere in a dark box using a semiconductor parameter analyzer (HP 4156C; Hewlett Packard). The transmittance of the glucose film on the glass substrate was measured with a UV-visible spectrophotometer (V-650, JASCO Corp.). The thicknesses of three organic materials (poly(methyl methacrylate) (PMMA), mannitol, and polyethyleneimine (PEI)) were measured with a spectroscopic ellipsometer (SE; Alpha SE).

3. Results and discussion

Figure 2(a) shows the optical transmittance of the glucose film on a glass substrate. The glucose films exhibited high transparency (over 80%) under the visible-light region from 390 to 700 nm. The glucose film deposited on a silicon substrate as the switching layer of the glucose-based RRAM is also shown in Figure 2(b). In addition, atomic force microscopy (AFM) analysis was carried out to investigate the surface characteristics of the glucose film with a \( 1 \times 1 \) μm² scan size, as shown in Figure 3. It was observed that the glucose film had a very smooth surface (root mean square (RMS): 0.326 nm) compared with SiO₂ (RMS: 0.344 nm). In general, the surface roughness of the thin film plays a crucial role in determining the electrical contact characteristics. The AFM results indicate the good surface characteristics of the glucose film.
Figure 2. Transmittance of the glucose film and (a) glucose film deposited on glass and (b) on a silicon substrate.

Figure 3. AFM results for (a) the SiO₂ surface and (b) the glucose surface.

Figure 4. I–V switching curves of the glucose-based RRAM. The fabricated glucose-based RRAM showed a bipolar switching behavior when a DC voltage bias with a ∼10 high-resistance state (HRS)/low-resistance state (LRS) ratio was swept, as shown in Figure 4. The bottom electrode, which was silicon substrate, was grounded while the voltage bias was being applied to the Al top electrode with a 1 mA compliance current (CC). Compliance current is generally essential for preventing the permanent breakdown of RRAM devices [13]. Initially, the glucose-based RRAM showed HRS, which is called ‘OFF state.’ When voltages from 0 to a positive value were applied, the current steadily increased, and then an abrupt current increase was observed when the bias
reached the threshold voltage (∼1.8 V), defined as V_{set}. After the SET process, the resistance state of the RRAM devices switched from HRS to LRS, which is called ‘ON state.’ By applying voltages from 0 to a negative value, a current decrease from LRS to HRS at about −1 V, defined as V_{reset}, was observed. The HRS was maintained after the RESET process by sweeping from a negative value to 0. The double logarithmic plot and linear fitting of the I–V switching curve were carried out as shown in Figure 5 to further confirm the conduction mechanism of glucose-based RRAM. In the LRS region, Ohmic conduction (I ∝ V) with a ∼1 slope demonstrating conductive filament formation in the device can be confirmed by the result of linear dependence according to the voltage variation [14–17]. On the other hand, the HRS region exhibited three different conduction behaviors with different slopes, demonstrating space-charge-limited conduction: the Ohmic conduction region (I ∝ V) with a ∼1 slope at a low voltage, the Child’s law region (I ∝ V^2) with a ∼2 slope at a high voltage, and the rapid-current-increase region at the SET voltage [14–16]. These results prove that the conduction mechanism is based on the conductive filament near the interface [18–21]. Based on the aforementioned results, the operation mechanism is schematically illustrated in Figure 6. The glucose-based RRAM initially exhibited a high-resistance characteristic due to the oxidized Al (AlO_x) insulator at the interface between the Al and the glucose film. The oxygen ions in the AlO_x layer moved to the upper-interface region of the Al electrode when a positive forming voltage was applied to the top Al electrode, and local oxygen vacancy (V_O) filaments were formed at the same time, indicating LRS. To rupture the conductive V_O filaments, a negative voltage was applied to the top Al electrode so that the oxygen ions would move downward, indicating HRS. In addition, it was confirmed that the glucose-based RRAM exhibited stable data reliability with endurance and retention characteristics at a 0.2 V read voltage, as shown in Figure 7(a,b). Then representative organic materials like PMMA, mannitol, and PEI were prepared as switching layers of RRAM devices, to investigate the effect of the interface between the Al top electrode and the

![Figure 6. Switching mechanism of glucose-based RRAM.](image)

![Figure 7. (a) Endurance characteristic for the 100 set-reset cycling test. (b) Retention characteristic for 10^4 seconds.](image)
glucose film. Before the formation of the switching layers, SE measurement was performed to define the thicknesses of the organic materials similar to the glucose film (~56 nm). As shown in Figure 8, the thickness of the three organic materials were confirmed. The fabricated organic-based RRAM showed general bipolar switching characteristics similar to those of the glucose-based RRAM, as shown in Figure 9. Based on these results, it can be said that the oxide layer formed by the redox reaction between an oxidizable Al electrode and an organic material is a critical switching mechanism. Al is known to be easily oxidized by moisture or oxygen molecules even in a stable ambient atmosphere, due to its high oxygen affinity [22]. In addition, many organic materials tend to oxidize with the oxidizable metals at the junction due to the many oxygen functional groups in such materials [22].

Figure 10 shows the results of the degradability test that was conducted using a petri dish filled with water for transient and implantable electronics with

![Figure 8](image1.png)

Figure 8. Film thicknesses of various organic materials determined using SE measurement: (a) PMMA; (b) mannitol; and (c) PEI.

![Figure 9](image2.png)

Figure 9. I–V switching characteristics of RRAM with various organic materials: (a) PMMA; (b) mannitol; and (c) PEI.
biocompatibility. Water-soluble paper and magnesium (Mg) were prepared for the substrate and electrode, which are harmless and can be readily dissolved in water. The water-soluble paper was composed of sodium carboxymethyl cellulose, and Mg is widely used in the field of transient and implantable electronics due to its biocompatibility and biodegradability as well as its sufficient electrical conductivity [1]. The glucose-based RRAM fabricated on a sodium carboxymethyl cellulose substrate rapidly dissolved in water after 120 seconds due to the disintegration of the RRAM devices, as shown in Figure 10. Based on the study results, it was verified that glucose-based RRAM can be used for transient and implantable electronics for future medical applications.

Thus, this research demonstrated that glucose-based RRAM is highly promising for use in the next-generation implantable, biocompatible, and eco-friendly transient electronics.

### Disclosure statement

No potential conflict of interest was reported by the authors.

### Funding

This work was supported by a National Research Foundation of Korea (NRF) grant funded by the South Korea government (MSIT) [grant number 2017R1A2B3008719].

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