

Honey-CNT based Resistive Switching Device for Neuromorphic Computing Applications

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Abstract— Modern computing applications increasingly rely on technologies in artificial intelligence, machine learning, and big data analytics. These applications often demand more powerful and energy-efficient hardware. Resistive switching random access memory (ReRAM) has emerged as a promising solution to satisfy both the storage and computing needs. In this paper, a natural organic honey film embedded with carbon nanotube (CNT) was fabricated into a resistive switching device, and the resistive switching behaviors were investigated. Endurance test results show the cycle-to-cycle variation of set and reset voltages. On/Off ratio in retention test was found to be in the order of $\sim 10^5$ which proves its potential as a non-volatile memory device to support neuromorphic computing applications. This research opens up opportunities to execute big data and machine learning applications with modest energy consumption and minimal electronic waste.

Keywords—Neuromorphic computing, machine learning, nonvolatile memory, resistive switching, energy-efficient computing

I. INTRODUCTION

The invention of transistor technology has become one of the greatest scientific discoveries in human history. However, according to Moore's law transistor based conventional von neumann computer architecture is getting closer to its atomic limits, and newer technology with better performance and higher energy efficiency is becoming increasingly sought after, especially for supporting data intensive and machine learning applications. With this in mind, extensive research has been carried out to develop neuromorphic computing systems which can mimic behaviors of human brain. As human brain is the most efficient computational entity, using only 20 watts of energy for computations, where its counterpart, i.e., the conventional computer, uses energy in the range of megawatts.

Such neuromorphic system requires hardware that can emulate biological neurons in order to execute machine learning workflows. Resistive switching random access memory (ReRAM) is a promising candidate for data storage technology in neuromorphic computing system due to its low power consumption, reliability, and fast switching characteristics. But after these ReRAM devices exceed their expected life usage, their disposal produces huge amounts of toxic electronic waste that is harmful to the environment and human health. Therefore, ReRAM made from natural organic materials is gaining popularity because they are environmentally friendly, biodegradable, comparatively low cost, and renewable [1, 2]. In this paper we fabricated a ReRAM device from natural organic honey embedded with carbon nanotubes, honey-CNT ReRAM, and reported its resistive switching characteristics. A machine learning

algorithm was also developed to predict device fabrication parameters.

II. EXPERIMENTAL

Fig. 1(a) shows the schematic design of the honey-CNT ReRAM device. To fabricate the device, the pure honey was mixed with De-Ionized (D.I.) water to make a 30% solution. Then, as-received single wall CNT powders with a 0.2 wt% concentration were dispersed into the honey solution in an ultrasonic bath for 60 minutes. One glass slide (2.5 cm $\times$ 2.5 cm) was cleaned in a chemical bath of acetone, IPA, and D.I. water, followed by the deposition of a 100 nm-thick ITO film as the bottom electrode. Next, honey-CNT solution was spin-coated on top of the ITO film at 3000 rpm for 60 s and baked at 90 $^{\circ}$ C for 8 hours to dry the honey-CNT film. Finally, a 100 nm-thick Al film was deposited as top electrodes through a circular stencil mask with varying diameters in the range of 100 μ m to 500 μ m. Fig. 1(b) shows the fabrication process flow, and the device is shown in Fig. 1(c).

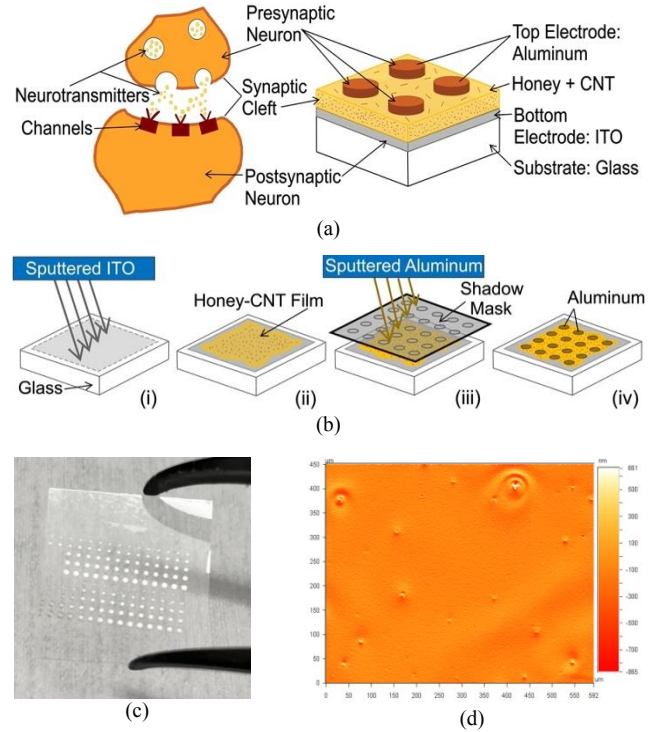


Fig. 1: (a) Schematic diagram of a biological synapses with a honey_CNT based resistive switching device. (b) Device fabrication process flow. (c) Photograph of the honey-CNT ReRAM device. (d) Surface morphology of honey-CNT film measured by an optical surface profiler.

III. RESULT AND DISCUSSION

Electrical testing was performed on a signatone probe-station with a Keithley 4200 Semiconductor Characterization System in air and at room temperature. An optical surface profiler (Wyko NT1100) was used to examine the surface morphology of the honey-CNT film. Fig. 1(d) shows that CNTs are agglomerated in the honey-CNT film due to strong van der Waals force in CNT clusters. I-V measurements were carried out by applying a bias to the top Al electrode while keeping the bottom ITO electrode grounded. Four voltage sweeps were applied as numbered in Fig 2(a). Initially, the ReRAM device was in high resistance state (HRS) or “OFF” state. After applying the first positive sweep I, the device changed to low resistance state (LRS), also called “ON” state, at 2V (V_{Set}). This transition from HRS to LRS is called the “writing” process. In the subsequent sweeps II and III, the device holds this “ON” state. At the end of sweep III at -1.2V (V_{reset}), the device changes from LRS to HRS, also known as the “erasing” process. Fig. 2(a) shows that the honey-CNT device shows bipolar and rewritable resistive switching nature without any specific form voltage.

Next, set (V_{set}) and reset (V_{reset}) voltage values for 200 switching cycles were recorded to measure the endurance performance, Fig. 2(b) presents the cumulative probability of V_{set} and V_{reset} . Average and standard deviation of SET and RESET values were calculated as 1.61 ± 1.01 and -1.09 ± 0.62 with a coefficient of variation is 0.63 for set and 0.56 for reset.

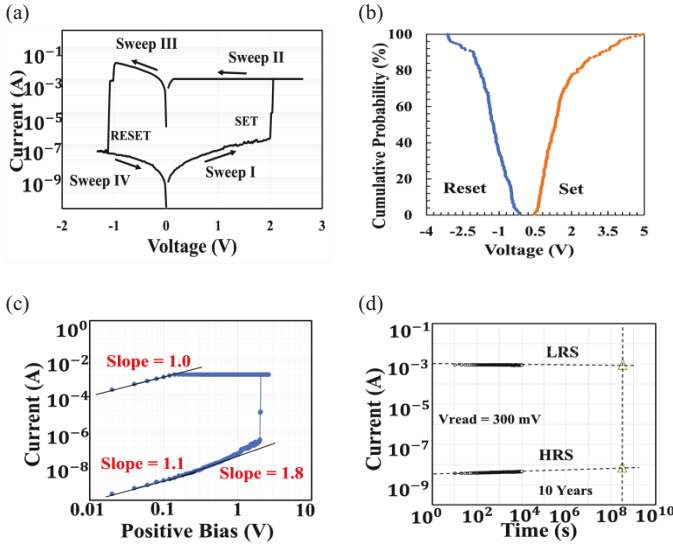


Fig. 2: (a) A bipolar switching cycle of Al/honey-CNT/ITO ReRAM device. (b) Probability distribution of V_{set} and V_{reset} voltages. (c) I-V curves drawn on double logarithmic scale. (d) Data retention characteristics for 10^4 s.

In Fig. 2(c), I-V curve of the forward bias region is re-plotted in log-log scale with linear fitting to explain the current conduction mechanism of the device. Unity slope of LRS current indicates that conduction mechanism follows Ohm’s law with resistance of filament conductive paths between top and bottom electrode due to the electrochemical redox of the top Al electrode. In HRS state slope was unity in low voltage range but increased to 1.8 as voltage get close to V_{set} . This

trend indicates that conduction mechanism in HRS is dominated by space charges limited conduction (SCLC) model.

It is well expected a nonvolatile memory device should be able to maintain its memory state for ten years. Data retention tests have been done on the device by applying a continuous read voltage of 300 mV for 10^4 s with the LRS and HRS current recorded at every 10s and then extrapolated for 10 years. It can be seen from Fig. 2(d) that the LRS current was found stable around 0.9 nA, whereas the HRS current had only a gradual increase from 3.7 nA to 4.9 nA for the entire 10^4 s. When both currents were projected for 10 years, the ON/OFF ratio was found to be maintained at 4.7×10^5 , which is larger than previously reported pure honey-ReRAM and proves better data retention ability [3].

These initial results on the nonvolatile behavior of the honey-CNT ReRAM device demonstrate its potential in implementing neural networks. In future work, we will develop a crossbar architecture in which an array of the ReRAM devices is used to emulate an artificial neural network. Specifically, synaptic weights are stored as the conductance states and the synaptic efficacy is realized following Ohm’s law with current flow through the device under a read voltage. This architecture will emulate synaptic efficacy by applying an input read voltage V to mimic synaptic input for neuronal activation on $N \times N$ ReRAM devices in the crossbar, with sum of the individual current flowing through each device to form the synaptic output. This work will provide a foundation for supporting machine learning algorithms using natural organic ReRAM devices.

CONCLUSION

In summary, an Al/honey-CNT/ITO ReRAM device was fabricated and test results showed bipolar resistive switching behavior with nonvolatile memory characteristics. Retention test results confirm that device is stable for a projection of 10 years, and endurance tests showed that device can switch 200 cycles. It is anticipated that ReRAM technology based on the environmentally-benign and biodegradable honey material will be a strong candidate for use in future neuromorphic computing systems to support big data and machine learning applications, leading to a greener computing paradigm for the big data era.

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