Materials Letters 308 (2022) 131169

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

Study of synaptic properties of honey thin film for neuromorphic systems

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A R T I C L E I N F O

Keywords:
Honey
Bio-organic material
Synaptic device
Neural facilitation
Neuromorphic

A B S T R A C T

Besides conventional electrical properties, materials for emerging artificial synaptic devices in brain-inspired neuromorphic systems need to have properties analogous to those of biological synapses, such as synaptic plasticity. In this work, we investigated, for the first time, the synaptic properties of a natural bio-organic material – honey. The honey film was sandwiched between Ag and ITO to form a structure resembling biological synapse. Neural facilitation, an essential synaptic plasticity, was demonstrated by honey thin film with a larger facilitation index, wider interval time range and higher dynamic filtering gain than other natural bio-organic materials. The results indicate that honey is promising for renewable artificial synaptic devices.

1. Introduction

Brain-inspired neuromorphic computing has emerged as one of the solutions to overcome the von Neumann bottleneck in energy consumption. Such analog systems require artificial synaptic devices, the fundamental hardware components, to have properties analogous to those of biological synapses. The resistive random access memory (RRAM) based artificial synaptic devices [1] resemble "point-to-point" connected biological synapses and are able to mimic synaptic functions because of their tunable resistance. Inorganic, polymer, and natural bio-organic materials [2] have been investigated as the key resistive switching layer in RRAM. Among these materials, natural bio-organic materials are sustainable, biodegradable, environmentally and biologically friendly for "green" artificial synaptic devices.

RRAM based on a natural bio-organic material – honey thin film has been demonstrated in our previous report [3]. In this paper, we study for the first time the neural facilitation, an essential synaptic plasticity, in honey thin film. Neural Facilitation, also known as paired-pulse facilitation (PPF), is an important short-term plasticity [4] for neural tasks such as learning, information processing, sound or visual source localization, etc. Compared with RRAM and transistors based on other natural bio-organic materials [5–9], honey RRAM devices demonstrated a larger PPF index, wider interval time range, and higher gain in high-pass synaptic filtering. These results suggest that honey is promising for the development of artificial synaptic devices in renewable neuromorphic systems.

2. Experimental

A glass slide was used as the substrate and cleaned in an ultrasonic bath by acetone, isopropyl alcohol and D.I. water. An ITO thin film with a sheet resistance of 10 Ω/sq was deposited on the glass as the bottom electrode (BE) through a stencil mask. Commercial honey was mixed carefully with D.I. water for a 30% concentration by weight and without honey crystal and air bubbles. The honey solution was spin-coated on the ITO/glass at 1000 rpm for 90 s, followed by drying on a hotplate at 90 °C for 9 h in air. A 100 nm-thick Ag film was sputtered as the top electrode (TE) through the same stencil mask rotated by 90° to form a crossbar array. Schematic and microscopic images of the Ag/honey/ITO crossbar RRAM and its resemblance to a biological synapse are illustrated in Fig. 1.

Surface roughness and morphology of the dried honey film were characterized by AFM and SEM, and the thickness was measured by a stylus surface profiler. Switching and PPF characterization was performed on a probe-station at room temperature in air using a semiconductor characterization system, an arbitrary function generator and an oscilloscope. The bias voltages were applied on the TE and ground on the BE.

3. Results and discussion

The SEM image in Fig. 2(a) was taken at the edge of the honey film on the glass substrate. Thickness of the dried honey film was measured with an average value of 2.5 μm after 10 scans along the edge by surface

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https://doi.org/10.1016/j.matlet.2021.131169
Received 30 September 2021; Received in revised form 20 October 2021; Accepted 27 October 2021
Available online 7 November 2021
0167-577X/

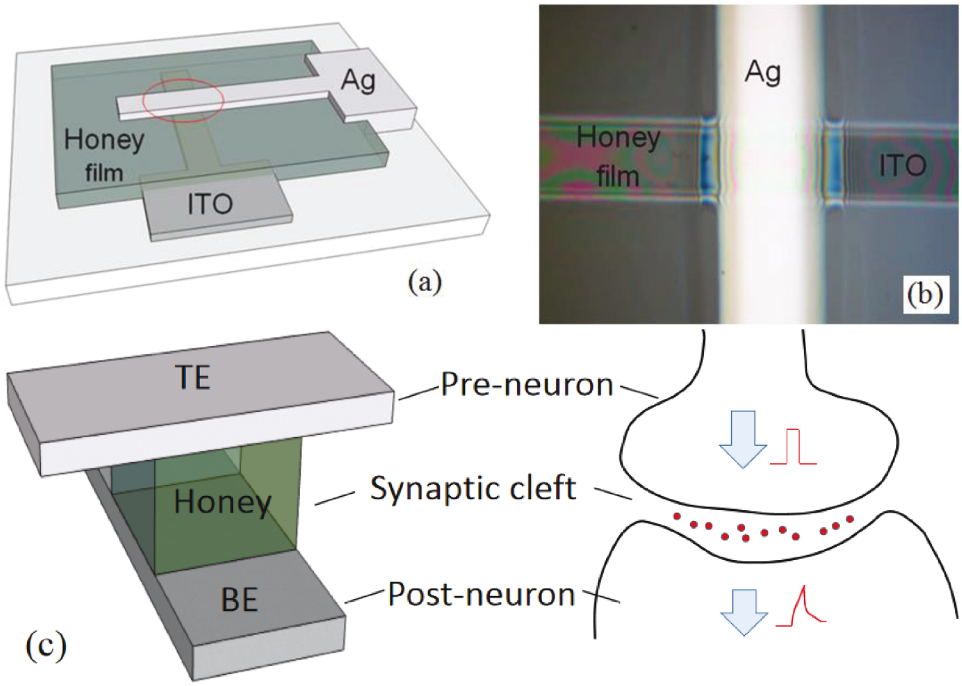

Fig. 1. (a) Schematic crossbar structure of Ag/honey/ITO RRAM and (b) microscopic image (×500) of the device after fabrication. (c) The cross-point of honey RRAM and its resemblance to a biological synapse.

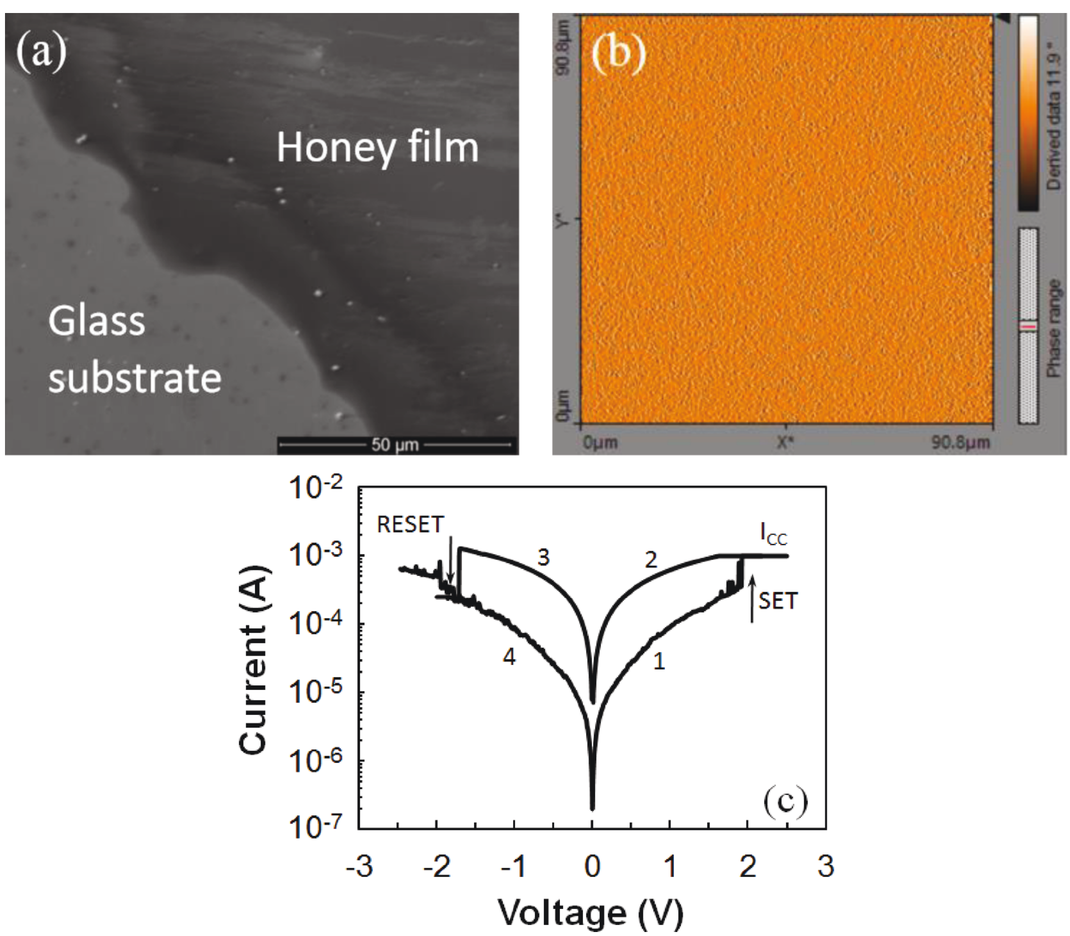

Fig. 2. (a) SEM images of the honey film on a glass substrate. (b) AFM tapping mode images of the dried honey film without crystals. (c) Analog switching characteristics of Ag/honey/ITO RRAM device.

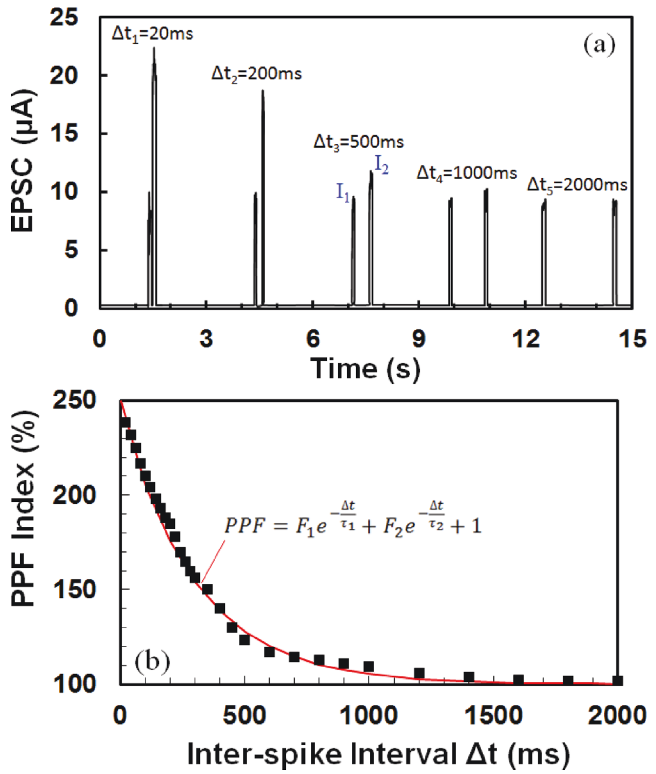

Fig. 3. PPF behaviors of the honey RRAM device with (a) postsynaptic EPSC triggered by a pair of presynaptic spikes with different interval times and (b) PPF index (black squares) as a function of inter-spike interval time. The red curve represents the exponential fit by Eq. (2).

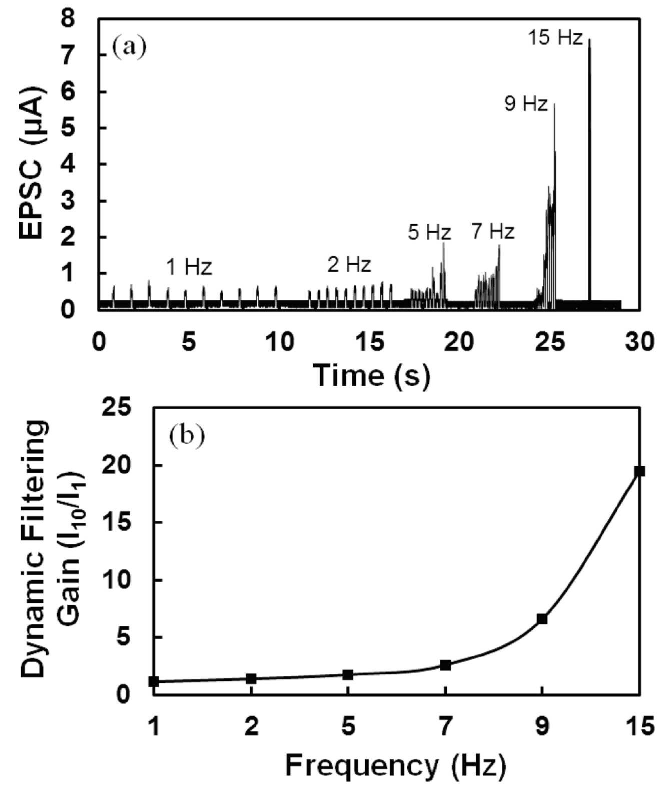

Fig. 4. (a) Dynamic filtering of honey RRAM triggered by a presynaptic spike train with 10 voltage pulses at different frequencies. (b) The dynamic filtering gain as a function of the frequency.

profiler. Surface roughness was measured in a 90 μm × 90 μm area as shown in Fig. 2(b) with smooth and uniform honey film surface. The average (R_a) and root mean square (R_{rms}) roughness of the honey film were 35 nm and 42 nm, respectively. With sufficient mixing, honey can dissolve in D.I. water completely and no honey crystal was visible in the dried honey film. The typical I-V characteristics of the Ag/honey/ITO RRAM synaptic device under DC sweeping voltage at a rate of 1 V/s is shown in Fig. 2(c) with the voltage sweep sequence numbered. A current compliance of 1 mA was applied to avoid current overshooting in the positive voltage sweep. The device demonstrated analog bipolar switching characteristics with current change gradually in both SET and RESET process, which is different from the digital switching of our previously reported Cu/honey/Cu_xO [3] with abrupt current change. Such analog switching is essential for RRAM to mimic synaptic plasticity. The current conduction is attributed to the electrochemical formation and dissolution of metal filaments in honey film due to the redox process of top metal electrode [10].

Fig. 3 shows the PPF demonstrated by honey RRAM. Two sequential voltage pulses (0.5 V, 100 ms) with interval time Δt from 20 to 2000 ms emulated pre-neuron spikes. The current in the honey film emulated the excitatory postsynaptic current (EPSC) in the post-neuron. Fig. 3(a) shows clearly PPF by the larger second than the first EPSC spike till $\Delta t = 2000$ ms. PPF effect is quantified by the PPF index, I_2/I_1, the absolute amplitudes of the first and the second EPSC spike, respectively. Fig. 3(b) summarizes the PPF index with the interval time Δt. With a larger PPF index, a higher postsynaptic weight enhancement can be obtained when Δt reduces, a similar trend to that observed in biological systems [11–12]. Compare to other natural organic materials such as chicken albumen [5], the honey demonstrates PPF effect in a larger Δt range. Also, at the interval time of 20 ms, the honey device shows the PPF index comparable to chicken albumen device [5] but much larger than lignin device [7]. It is also noted that the power dissipated in the honey RRAM is about 10 μW and energy is about 200 nJ, comparable with other CMOS and memristor based artificial synaptic devices [13]. In biological synapses, PPF index can be modeled by a double exponential decay [14,15]: $PPF = F_1 e^{-\frac{\Delta t}{\tau_1}} + F_2 e^{-\frac{\Delta t}{\tau_2}} + 1$, where F_1 and F_2 are the initial facilitation magnitudes of the rapid phase and slow phase, τ_1 and τ_2 are the characteristic relaxation times of the rapid phase and slow phase. The modeled PPF was plotted as the red curve in Fig. 3(b), which fits the measurements very well. The PFF index of honey RRAM decays with a fast phase ($F_1 = 5\%$, $\tau_1 = 40$ ms) and a slow phase ($F_2 = 145\%$, $\tau_2 = 303$ ms), agreeing with the biological synapses at the normal levels of extracellular calcium concentration $[Ca^{2+}]_e$ [16,17].

Since the synaptic weight is activity-dependent, synapses can act as dynamic filters for information transmission [18,19] depending on the frequency: high (low)-pass filters when the synapse selectively responds to high (low)-frequency signals. Fig. 4(a) shows the EPSC responses to a 10-pulse spike train (0.6 V, 100 ms) at different frequencies. The peak value increases with the frequency. The gain of dynamic filtering is defined as I_{10}/I_1, the ratio of the peak amplitudes between the tenth spike (I_{10}) and the first spike (I_1). Fig. 4(b) summarizes the gain at different frequencies. The increased gain values indicate that the honey RRAM can act as a dynamic high-pass frequency filter-like synapse with potential for applications in neural network and algorithm level such as non-linear autonomous learning component in neuromorphic systems [20]. The results also demonstrates the potential that higher gains can be achieved from the honey RRAM (20 at 15 Hz) than other natural bio-organic materials such as chicken albumen (2.5 at 15 Hz) [5] and chitosan (3.5 at 15 Hz) [6]. As biological synapses have both short term and long term plasticity, besides PPF and filter dynamics of short term plasticity, the long term plasticity behaviors by honey RRAM are currently under investigation.

4. Conclusions

This work explored the potential of honey for artificial synaptic devices. The Ag/honey/ITO RRAM demonstrated bipolar analog switching behaviors. PPF and synaptic filtering were emulated, with a larger PPF index, wider interval time range, and higher dynamic filtering gain than other natural bio-organic materials. The two exponential phases of PPF demonstrated by honey synaptic device is analogous to the PPF of biological synapses. Our results prove that as a natural bio-organic material of sustainable, biodegradable, environmentally and biologically friendly, honey is promising for developing artificial synapses in renewable neuromorphic systems.

CRediT authorship contribution statement

Brandon Sueoka: Formal analysis, Methodology, Investigation, Writing – original draft. **Kuan Yew Cheong:** Formal analysis, Writing – review & editing. **Feng Zhao:** Supervision, Conceptualization, Formal analysis, Project administration, Resources, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Feng Zhao acknowledges the support from National Science Foundation, United States (ECCS-2104976).

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