Memristive Properties of Mushrooms

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Abstract

Memristors close the loop for I-V characteristics of the traditional, passive, semi-conductor devices. Originally proposed in 1971, the hunt for the memristor has been going ever since. The key feature of a memristor is that its current resistance is a function of its previous resistance. As such, the behaviour of the device is influenced by changing the way in which potential is applied across it. Ultimately, information can be encoded on memristors. Biological substrates have already been shown to exhibit some memristive properties. However, many memristive devices are yet to be found. Here we show that the fruit bodies of grey oyster fungi Pleurotus ostreatus exhibit memristive behaviours. This paper presents the I-V characteristics of the mushrooms. By examination of the conducted current for a given voltage applied as a function of the previous voltage, it is shown that the mushroom is a memristor. Our results demonstrate that nature continues to provide specimens that hold these unique and valuable electrical characteristics and which have the potential to advance the field of hybrid electronic systems.

1 Introduction

Originally proposed by Chua in 1971 [8], the memristor poses a fourth basic circuit element, whose characteristics differ from that of R, L and C elements. Memristance has been seen in nano-scale devices where electronic and ionic transport are coupled under an external bias voltage [31]. Strukov et al. posit that the hysteretic I-V characteristics observed in thin-film, two-terminal devices can be understood as memristive. However, this is observed behaviour of devices that already have other, large signal behaviours.

Finding a true memristor is by no means an easy task. Nevertheless, a number of studies have turned to nature to provide the answer, with varying success. Memristive properties of organic polymers were discovered well before the ‘official’ discovery of the memristor was announced in [31]. Memristive properties of organic polymers have been studied since 2005 [11] in experiments with hybrid electronic devices based on polyaniline-polyethylenoxide junction [11]. Memristive properties of living creatures and their organs and fluids have been demonstrated in skin [25], blood [21], plants [33] (including fruits [32]), slime mould [13], tubulin microtubules [10] [7].

This paper presents a study of the I-V characteristics of the fruit bodies of the grey oyster fungi Pleurotus ostreatus. Why fungi? Previously we recorded extracellular electrical potential of oyster’s fruit bodies, basidicarps [1] and found that the fungi generate action potential like impulses of electrical potential. The impulses can propagate as isolated events, or in trains of similar impulses. Further, we demonstrated, albeit in numerical modelling, that fungi can be used as computing devices, where information is represented by spikes of electrical activity, a computation is implemented in a mycelium network and an interface is realised via fruit bodies [2]. A computation with fungi might not be useful per se, because the speed of spike propagation is substantially lower than the clock speed in conventional computers. However, the fungal computation becomes practically feasible when embedded in a slow developing spatial process, e.g. growing architecture structures. Thus, in [3] we discussed how to: produce adaptive building constructions by developing structural substrate using live fungal mycelium, functionalising the substrate with nanoparticles and polymers to make mycelium-based electronics, implementing sensorial fusion and decision making in the fungal electronics.
Why we are looking for memristive properties of fungi? A memristor is a material implication \[5, 23\] and can, therefore, be used for constructing other logical circuits, stateful logic operations \[5\], logic operations in passive crossbar arrays of memristors \[23\], memory aided logic circuits \[22\], self-programmable logic circuits \[21\], and, indeed, memory devices \[10\]. If strands of fungal mycelium in a culture substrate and the fruit bodies show some memristive properties then we can implement a large variety of memory and computing devices embedded directly into architectural building materials made from the fungal substrates \[2\].

The rest of this paper is organised as follows. Section 2 details the experimental set up used to examine the I-V characteristics of fruit bodies. Section 3 presents the results from the experimentation, with further discussion of voltage spiking provided in section 3.2. A discussion of the results is given in section 4 and finally conclusions are given in section 5.

2 Experimental Set Up

We used grey oyster fungi \textit{Pleurotus ostreatus} (Ann Miller’s Speciality Mushrooms Ltd, UK) cultivated on wood shavings. The iridium-coated stainless steel sub-dermal needles with twisted cables (Spes Medica SRL, Italy) were inserted in fruit bodies (Fig. 1) of grey oyster fungi using two different arrangements: 10 mm apart in the cap of the fungi (cap-to-cap), Fig. 1(a) and translocation zones (cap-to-stem), Fig. 1(b) I-V sweeps were performed on the fungi samples with Keithley Source Measure Unit (SMU) 2450 (Keithley Instruments, USA) under the following conditions: [-500 mV to 500 mV, -1 V to 1 V] with the samples in ambient lab light (965 Lux). Varying the step size of the voltage sweep allowed testing the I-V characteristics of the subject at different frequencies. Electrodes were arranged in two different methods: both electrodes approximately 10 mm apart in the cap of the fruit body (Fig. 1(a)); and one electrode placed in the cap with the other electrode placed in the stem (Fig. 1(b)). The voltage ranges are limited so as not to cause the electrolysis of water. Each condition was repeated at least six times over the samples. Voltage sweeps were performed in both directions (cyclic voltammetry) and plots of the I-V characteristics were produced.
3 Results

3.1 I-V characterisation

Fruit body samples are shown to exhibit memristive properties when subject to a voltage sweep. The ideal memristor model (Fig. 2) is shown to display ‘lobes’ on the I-V characterisation sweeps, indicating that the current resistance is a function of the previous resistance — hence a memristor has memory. For the purposes of analysis, graphs are referred to by their quadrants, starting with quadrant one as the top right and being number anti-clockwise.

The ideal memristor model has a crossing point at 0V, where theoretically no current flows. From Figs. 3 and 4, it can be seen that when 0 V is applied by the source meter, a reading of a nominally small voltage and current is performed. The living membrane is capable of generating potential across the electrodes, and hence a small current is observed.

While the sample under test is subjected to a positive voltage (quadrant 1), it can be seen there is nominally a positive current flow. Higher voltages result in a larger current flow. For an increasing voltage sweep there is a larger current flow for the corresponding voltage during a negative sweep.

Similarly, in quadrant 3 where there is a negative potential across the electrodes, the increasing voltage sweep yields a current with smaller magnitude than the magnitude of the current on a negative voltage sweep.

Put simply, the fruit body has a resistance that is a function of the previous voltage conditions.

By applying averaging to the performed tests, a clear picture is produced that demonstrates for a given set of conditions, a typical response shape can be expected (Figs. 5 and 6). The stem-to-cap placement of the electrodes in the fruit body yields a tighter range for the response (figures 5(b) and 6(b)). This can be expected due to the arrangement of the transportation pathways, so-called translocation zone distinct from any vascular hyphae [29, 20], in the fruit body which run from the edge of the cap and down back through the stem to the root structure (mycelium). Cap-to-cap placement of the electrodes applies the potential across a number of the solutes translocation pathways and hence yields a wider range of results. However, for all results, it is observed that the positive phase of the cyclic voltammetry produces a different conduced current than the negative phase.

Reducing the step voltage step size (by ten fold) for the I-V characterisation is synonymous to reducing the frequency of the voltage sweep. Decreasing the sweep frequency of the voltage causes the chances of “pinching” in the I-V sweep to increase, as seen in quadrant 1 of figure 7.

3.2 Spiking

It is observed from Figs. 3 to 4 that portions of the cyclic voltammetry result in oscillations in the conduced current, or spiking activity. Oscillations occur most prominently on the positive phase of the cyclic voltam-
Figure 3: Raw data from cyclic voltammetry performed over -0.5 V to 0.5 V. (a) Cap-to-cap electrode placement. (b) Stem-to-cap electrode placement.
Figure 4: Raw data from cyclic voltammetry performed over -1 V to 1 V. (a) Cap-to-cap electrode placement. (b) Stem-to-cap electrode placement.
Figure 5: Average grey oyster fungi fruit bodies I-V characteristics for cyclic voltammetry of -0.5 V to 0.5 V. (a) Cap-to-cap electrode placement. (b) Stem-to-cap electrode placement.

Figure 8 demonstrates the spiking frequency of a single repeat of the cyclic voltammetry performed between -0.5 V and 0.5 V with the electrodes in a cap-to-cap arrangement. It is shown in the figure that the voltage interval between spikes in an oscillation period are less than 0.06 V. Figure 9 concatenates the data for all repeats of the cyclic voltammetry performed under four different conditions. It is clearly shown that in cap-to-cap arrangements the voltage interval between spikes is less than when the electrodes are in a translocation arrangement. Any spikes that occur when the voltage interval becomes large can be taken as not occurring during a period of oscillation in the sweep, instead they occur infrequently and randomly during the sweep.

Reducing the frequency of the voltage sweep (Fig. 7) also has the effect of removing the current oscillations.
Figure 6: Average fruit bodies I-V characteristics for cyclic voltammetry of -1 V to 1 V. (a) Cap-to-cap electrode placement. (b) Stem-to-cap electrode placement.

Figure 7: I-V characteristics of fungi fruit bodies with the voltage step size set to 0.001 V.
Figure 8: The voltage interval of spikes in the I-V characteristics of the fruit body for a single run.
Figure 9: Concatenations of all spiking data from all data runs for four different test conditions. (a) voltammetry over -0.5 V to 0.5 V, cap-to-cap electrode arrangement. (b) voltammetry over -1 V to 1 V, cap-to-cap electrode arrangement. (c) voltammetry over -0.5 V to 0.5 V, stem-to-cap electrode arrangement. (d) voltammetry over -1 V to 1 V, stem-to-cap electrode arrangement. Legends omitted on (c) and (d) for clarity.
4 Discussion

Here we report the I-V characteristics of grey oyster fungi *Pleurotus ostreatus* fruit bodies. It is evident from the results that grey oyster fungi display memristive behaviour.

Although the fruit bodies typically do not demonstrate the “pinching” property of an ideal memristor [9], it can be clearly seen that the biological matter exhibits memory properties when the electrical potential across the substrate is swept. A positive sweep yields a higher magnitude current when the applied voltage is positive; and a smaller magnitude current when the applied voltage is negative.

Similar I-V characteristics have been experienced for slime mould [13] and apples [32]. The cyclic voltammetry experiments demonstrate that the I-V curve produced from these living substrates is a closed loop where the negative path does not match the positive path. Hence the fungi display the characteristics of a memristor. A similar conclusion is drawn for the microtubule experiments [6]. The microtubule exhibits different resistive properties for the same applied voltage depending on the history of applied voltages.

Additionally, the fruit bodies produce current oscillations during the cyclic voltammetry. This oscillatory effect is only observed on one phase of the voltammetry for a given voltage range which is, again, a behaviour that can be associated to a device whose resistance is a function of its previous resistance. This spiking activity is typical of a device that exhibits memristive behaviours. Firstly, it was reported in experiments with electrochemical devices using graphite reference electrodes, that a temporal dependence of the current of the device - at constant applied voltage - causes charge accumulation and discharge [12]. The spiking is also apparent in some plots, for a large electrode size, in experiments with electrode metal on solution-processed flexible titanium dioxide memristors [15]. A detailed analysis of types of spiking emerging in simulated memristive networks was undertaken in [14]. Repeatable observations of the spiking behaviour in I-V of the fungi is very important because this opens new pathways for the implementation of neuromorphic computing with fungi. A fruitful theoretical foundation of this field is already well developed [30, 18, 28, 27, 24, 19].

5 Conclusion

The fruit bodies of grey oyster fungi *Pleurotus ostreatus* were subjected to I-V characterisation a number of times, from which it was clearly shown that they exhibit memristive properties. Under cyclic voltammetry, the fruit body will conduct differently depending on the phase (positive or negative) of the voltammetry. This behaviour produces the classic “lobes” in the I-V characteristics of a memristor.

However, a biological medium, such as the fruit body of the grey oyster fungi presented here, will differ from that of the ideal memristor model since the “pinching” behaviour and size of the hysteresis lobes are functions of the frequency of the voltage sweep as well as the previous resistance. Typically, the biological medium generates its own potential across the electrodes, therefore, even when no additional potential is supplied by the SMU, there is still current flow between the probes.

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