Non-linear Bioelectronic Element: Schottky Effect and Electrochemistry

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Asymmetric electrical contact (gold and indium) was performed to the slime mold. Electrical characterization of such structure revealed rectifying behavior due to the Schottky effect and a hysteresis due to the electrochemical activity within the slime mold.

Keywords: Slime mold, Schottky effect, electrochemistry

Physarum polycephalum belongs to the species of order Physarales, subclass Myxogastromycetidae, class Myxomycetes, and division Myxostelida. It is a single cell with many diploid nuclei. In principle, plasmodium foraging behavior can be interpreted as a computation [1]. Plasmodium can solve computational problems with natural parallelism [2]. In addition, the slime mold can produce rhythmic electrical signals [2, 3], that can be considered as candidates for the clock generator of the biological computers.

As the most of the modern computers are based on the electrical signal, it is necessary to integrate the slime mold into such systems. Thus, the aim is to build a non-linear electronic elements with properties, depending also on the slime mold activity.

This short paper is dedicated to the realization of such element.

One of the simple ways of realization of non-linear elements is the formation of asymmetric structures. In particular, it is possible to organize a structure, where the material is placed between two electrodes, realized from the
metals with a significant difference in the work functions. In this case, a system, similar to the Schottky diode can be realized. Similar approach has been already successfully applied for the realization of threshold elements in systems [4-6], based on organic memristive devices [7-9].

Plasmodium of P. polycephalum is cultivated in plastic containers, on paper towels sprinkled with distilled water and fed with oat flakes (Asda’s Smart Price Porridge Oats, UK).

We have used gold and indium for the electrodes of the asymmetric structure as they have a significant difference in their work functions [4]. An image of the system under the measurements is shown in Fig. 1. After the growth in the direction of the attractor (food, left side of the image), the formed channel of the slime mold was contacted by the freshly cleaned indium material and gold wire. Measurements of the electrical characteristics were done with a Keithley 6514 system electrometer, interfaced with PC through a MatLab script. Cyclic voltage-current characteristics were measured in the following way. Measurements were started at 0 V bias voltage. Readouts of the current were performed after the 0.1 V increment of the applied voltage, with the time delay for the equilibration in the range 1-60 seconds.

At least 20 samples in the configuration, similar to that shown in Fig. 1 were prepared and investigated. Of course, the length, width and thickness of the slime mold channels were different for each experimental set up, as the system was in the living state during the experiments.

FIGURE 1
An image of the experimental setup for the study of cyclic voltage-current characteristics of the slime mold placed between asymmetric metal junctions (yellow substance in the center is a Physarum polycephalum).
Typical cyclic voltage-current characteristic of the system, shown in Fig. 1, is presented in Fig. 2 for the time delay of 1 second. All the investigated samples have revealed similar qualitative behavior: of course, the absolute values of the measured currents were different due to the difference in the length, width and thickness of the slime mold channels, as it was mentioned above.

Analysis of the characteristics, shown in Fig. 2 reveals the presence of some features, that we expected to realize – suppression of the conductivity for low voltage values of the characteristics in the direction of the positive bias and, in general, rectification features, that, as it must be, are more pronounced for the low values of the bias voltage. However, the characteristics, shown in Fig. 2 has also one important feature, that is impossible for a simple Schottky junction – the presence of the hysteresis.

First explanation coming in mind is the consideration of RC of the system. However, simple estimations of the observed values give a 0.02 mF for the capacity of the junction, that, considering the length between the electrodes (about 5 mm) seems hardly possible.

However, in order to be sure that the presence of the hysteresis cannot be attributed only to the RC of the system, the measurements with the increased delay between the voltage increment application and the current readout were performed.

FIGURE 2
Cyclic voltage-current characteristics measured on the structure, shown in Fig. 1 with the time delay of 1 second between the application of the voltage increment and readout of the current value.
Typical cyclic voltage-current characteristics with the delay of 60 seconds is shown in Fig. 3.

Disregarding the difference in the absolute values of the current, due to the above discussed reasons, the characteristics presents also suppression of the conductivity in the positive applied voltage branch and rectification. However, there is a difference with respect to the characteristics, shown in Fig. 2: the hysteresis in the positive branch is practically suppressed, while it is practically unchanged in the negative branch of the applied bias voltages. Therefore, the presence of the hysteresis in the realized and studied structures is very likely connected to the internal electrochemical processes, occurring in the slime mold. The last statement is also confirmed by the comparison of Fig. 2 and Fig. 3 – the most of biological electrochemical processes occur at negative potentials. Thus, increase of the delay time can result in reaching of the equilibrium in the positive bias voltage branch, while it cannot affect the internal activity of the living system, resulting in the preservation of the hysteresis in the negative bias voltage branch.

Concluding, we have realized a non-linear bioelectronic element with properties, that are a superposition of the features of the asymmetric junction with those, resulted from the internal electrochemical activity of the slime mold. Such behavior can establish a basis for the bio-computational systems,
where memorizing of the event is an essential part of the computation. The presence of the hysteresis, as in the case of memristive devices [10], will vary at different time scale the connectivity within the system, allowing learning and decision making. It seems very challenging to develop the work in order to make a comparison of features of the completely artificial systems with threshold elements [6, 11] with slime mold based system, where natural attractors and repellents can be inserted.

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