Organic memristive device as transistor: working principle and possible applications

Silvia Battistoni[*†], **Regina Burganova**[†‡], **Victor Erokhin**[*‡],
[*]Institute of Materials for Electronics and Magnetism,Parco Area della Scienze 37, Parma, Italy
[†]University of Parma, Parco Area della Scienze 7A, Parma, Italy
[‡]Institute of Fundamental Medicine and Biology, Kazan Federal University, Kazan, Russia

***Abstract*—We report results regarding the possibility of driving an organic memristive device as a transistor, so applying a modulatory gate voltage. Even if transistors and organic memristive device have different working principles, they share the same electrode structure (e.g. gate, source and drain electrode).**

For memristive standard operational mode, the gate electrode must be used just as reference electrode, biased to ground potential while, in this work, we explored the action of different bias on the output current between the drain and source electrodes.

Keyword– Organic Memristor; Transistor; organic electronics; Polyaniline

I. Introduction

The term memristor was used for the first time by Leon O. Chua in 1971 for describing a passive element, the resistance of which depends on the value of the charge that has passed through it [1]. Organic memristive devices are elements in which the active material is an organic one (i.e. polymers) and their working principle is based on the redox reactions in contact of conducting polymers (in particular Polyaniline (PANI)) and polyelectrolytes [2]. In a memristive configuration, two electrodes contact directly the PANI channel (Source -S- and Drain-D-) while the polyelectrolyte layers instead is biased to ground potential thanks to a reference electrode called Gate (G) [3]. Critical parameters for the performance of the organic memristor are thickness and density of the PANI layer since they strongly affect the diffusion of the ions, responsible of the working principle. The technique chosen for the PANI deposition is Langmuir-Schaefer technique since it allows us to control directly the surface density and the thickness of the sample.

On the other hand, transistors are well known circuital elements, widely used in a wide range of applications; in particular organic transistors (OFET, OECT [4]) offer a lot of possible applications since they can be deposited with low-cost solution-processing and direct-write printing, ideal for flexible substrates [5]. Briefly, even if the geometry of the two devices (memristor and transistor) is pretty similar, the action of the gate electrode is completely different since in OFET the gate electrode has to control the charge movement induced in the channel while in memristor it has to act as a reference electrode.

II. Materials and Method

The preparation of the samples was performed as reported in [2]. A solution of PANI (Sigma Aldrich Mw =100000) in

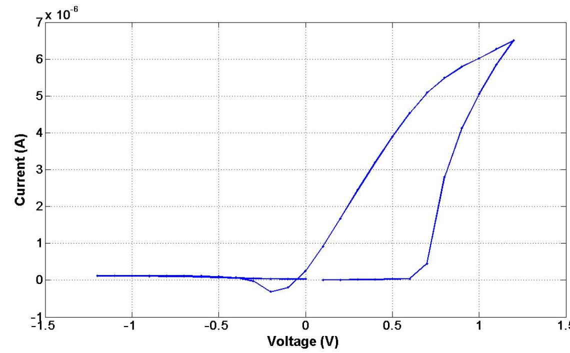


Fig. 1: Cyclic voltage output characteristic of a memristive device.

1-methyl-2-pyrrolidinone (Sigma Aldrich ACS reagent 99.0%) with the 10% of Toluene (AnalaR NORMAPUR ACS) is prepared with a concentration of 0.1 mg/mL and spread on the water subphase of the Langmuir trough. Once that the monolayer film is formed and separated in smaller sections with a special grid, it's transferred on a rectangular glass substrate with two evaporated chrome electrodes, by gently touching the monolayer with the insulating support. To obtain a proper film for the characterization it's necessary to deposit at least 48 monolayers, in order to have a film thick enough to have good conductive properties but thin enough to not reduce or decrease the diffusion of ions in its polymers chains. In this work the active layer of PANI is formed by depositing 60 layers of PANI, using the emeraldine base form. After the deposition, we doped the samples by dipping them twice in HCl (1 M), inducing the transformation in emeraldine salt conducting form. After the attachment of a small well of poly(ethylene-vinyl acetate), we fill it with our polyeletrolyte solution. This latter was obtained by dilution in water (with ratio of 1:2) of a water solution of polyethylene oxide (PEO)(Mw= of $810^6 Da$) prepared with a concentration of 20 mg/ml and doped with 0.1 M $LiClO_4$ (Sigma).

III. Results

A typical characterizations of the device are reported in Fig 1 and 2 where we performed a voltage sweep and a kinetic characterization acquiring the current that flows between the S and D electrode with a fixed gate voltage (0V).

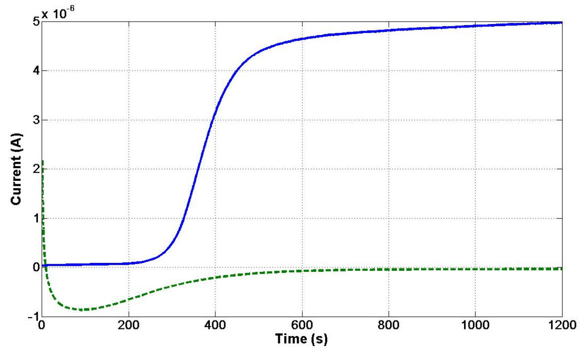


Fig. 2: Temporal current output of a memristive device at fixed applied voltages: -0.2V (dotted line) and 0.8 V (straight line)

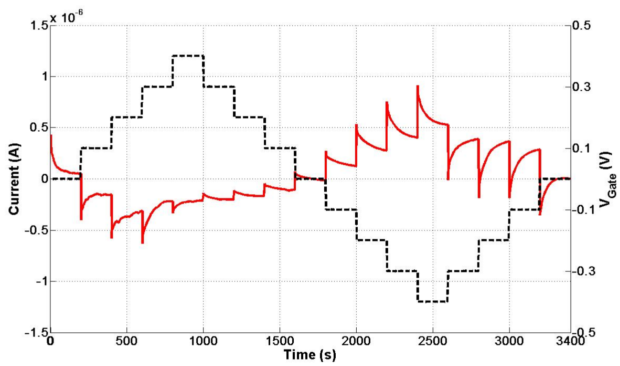


Fig. 3: Time response of the output current (I_{SD}) of the device (straight line) and of the gate voltage modulation (dotted line).

Two voltage values (0.6 V and -0.2V) determine the behaviour of the memristor, inducing the oxidation and consequently the increase of the conductivity or the reduction that decrease it, respectively. Voltage values included in the range between 0.2 V and 0.4 V don't effect the resistivity state of the device and so in this range the behaviour of the output current must be simply ohmic.

For our measurements we decided to apply a fixed voltage value of 0.2 V between S and D electrodes and to modulate the gate voltage varying its potential from -0.4 V $\div$ 0.4 V, in accordance with the working principle of a transistor. Gate potential was varied starting from 0 V and following a triangular shape with steps of 0.1 V each 200 s; the profile of the gate voltage and the resulting output current, acquired with a sampling period of 250 ms, are reported in Fig. 3.

The profile of the current curve shown Fig. 3 is the direct result of the gate modulation on the area of the PANI underneath the polyelectrolyte layer, defined in literature as Active Zone [3]. As reported in [3], the application of a fixed voltage between S and D electrodes induces a distribution of the potential along the PANI channel that results in a potential of the half of the original applied value in the centre of the Active Zone. When the Gate potential is kept constant to ground potential, this latter one together with the voltage

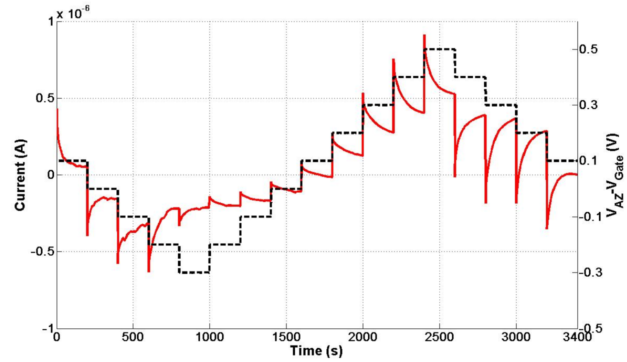


Fig. 4: Time response of the output current (I_{SD}) of the device (straight line) and $V_{\perp}$ voltage (dotted line).

in the Active Zone originate a voltage distribution also in the plane perpendicular to the PANI channel, that cross the interface between these two materials. A simple mathematical representation of this effect can be written with the equation:

$$V_{\perp} = \frac{V_{SD}}{2} - V_{Gate} \qquad (1)$$

where $\frac{V_{SD}}{2}$ is the half of the potential applied between source and drain (constant in our experiment) and V_{Gate} is the gate potential. Varying now the value of the gate potential, this induce a variation on the potential distribution at the interface between PANI and the polyeletrolyte following the Eq. (1) and it's shown in Fig. 4.

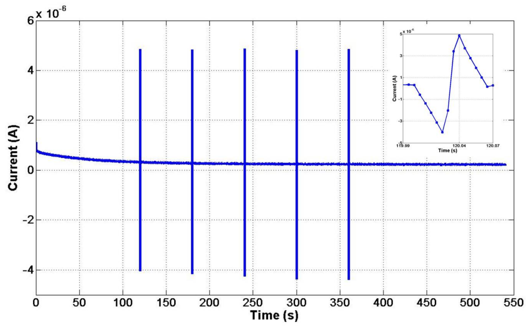
Looking at Fig. 4 we can make some observations:

1) I_{SD} has exactly the same trend of the $V_{\perp}$ curve, demonstrating that the proposed working principle model is in good agreement with the measurement.
2) During the first application of 0.3 V for the gate voltage ($V_{\perp}$= -0.2V) the SD current presents a strong decrease and this may be attributed to a partial reduction of the PANI channel.
3) As confirmation of the previous point, comparing the 3 steps in which we applied $V_{Gate} = 0V$ ($V_{\perp}$= 0.1V) we can underline a decrement of the current before and after the reduction process, while it remained constant after that.

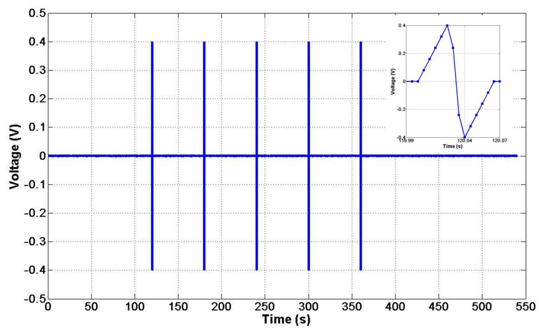
IV. Further Application

Since we demonstrated that even a small variation of the value of the gate voltage can affect significantly the output current of the device, one interesting and ambitious application of this acquisition mode of the memristor may be found in the revelation and acquisition of the neuronal firing signals [6].

To verify such possibility we applied to the gate a pulse voltage with a neural-like spike shape: starting from the bias voltage of 0V, we increase the potential with steps of 0.08 V until the reaching of 0.4V and then we rapidly decrease it until the value of -0.4V. From -0.4V we increase the potential coming back to 0V with steps of 0.08 V. Every step of potential



((a)) I_{SD}



((b)) V_{Gate}

Fig. 5: Time response of the output current (I_{SD}) of the device and V_{Gate} voltage; in the insets are shown two magnifications of the respective curves.

has a duration of 5 ms and so the total spike had a duration of 70 ms.

From the results shown in Fig. 5 is possible to observe that oscillation of the V_{Gate} voltage induce a variation in the I_{SD} current, even if the modulation is of small intensity ($\pm 80mV$) or of a short duration (5 ms).

V. Conclusion

In this paper, we reported a different operation mode of organic memristive devices. We demostrated that it's possible to drive such kind of elements as a transistor, so modulating its output current in function of the potential applied to the gate electrode and paving the way for a wide range of application in which organic memristive devices can be used in substitution of transistor. Furthermore we suggested and demonstrated that one possible application for it is the acquisition and magnification of signals even in the case of a neuronal signals.

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References

[1] L. O. Chua, "Memristor-the missing circuit element," *Circuit Theory, IEEE Transactions on*, vol. 18, no. 5, pp. 507–519, 1971.

[2] T. Berzina, A. Smerieri, M. Bernabò, A. Pucci, G. Ruggeri, V. Erokhin, and M. Fontana, "Optimization of an organic memristor as an adaptive memory element," *Journal of Applied Physics*, vol. 105, no. 12, p. 124515, 2009.

[3] V. Erokhin, "Organic memristors: basic principles," in *Proceedings of 2010 IEEE International Symposium on Circuits and Systems*, 2010.

[4] G. Tarabella, C. Santato, S. Y. Yang, S. Iannotta, G. G. Malliaras, and F. Cicoira, "Effect of the gate electrode on the response of organic electrochemical transistors," *Applied Physics Letters*, vol. 97, no. 12, p. 123304, 2010.

[5] Z. Bao *et al.*, "Materials and fabrication needs for low-cost organic transistor circuits," *Advanced Materials*, vol. 12, no. 3, pp. 227–230, 2000.

[6] D. Khodagholy, T. Doublet, P. Quilichini, M. Gurfinkel, P. Leleux, A. Ghestem, E. Ismailova, T. Hervé, S. Sanaur, C. Bernard *et al.*, "In vivo recordings of brain activity using organic transistors," *Nature communications*, vol. 4, p. 1575, 2013.