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Neuromorphic computing with memristors: preliminary experimental results.

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Abstract:

Individual memristors have been observed demonstrating neuron-like spiking patterns. It has been shown elsewhere that memristors provide superior modelling for neurons then the Hodgkin-Huxley model. Due to these results we expect memristors to be essential componentns for the construction of neuromorphic architectures. Simple circuits of two and three real world memristors were constructed and oscillatory and spike train behaviour was observed in them. An investigation into the minimal circuit size for complex behaviour was undertaken.

Introduction:

The memristor is the fourth fundamental circuit element which was predicted to exist from symmetry arguments in 1971[1]. It is a two terminal passive device. It is stateful and the internal state is related to past history of the device. Because of the memristor's ability to learn it has been proposed that the memristor could be a route to neuromorphic or brain-like hardware[2].

As the achievement of this is widely anticipated to lead to a step-change in not just computing, but science and even society itself (if it works we would be able to make a true machine intelligence which could enable us to answer fascinating philosophical questions about the nature of consciousness, intelligence and mankind). The relation between memristors and neuromorphic computing dates back to 1976 when Chua and Kang expanded the idea of the memristor to a memristive system (two state variables rather than one) and suggested that the Hodgkin-Huxley model of the nerve axon could be improved by in incorporating memristors in place of the non-linear time dependent resistors[3]: an idea that wasn't demonstrated until 2012[4,5].

Meanwhile the scientic community has concentrated on the idea of using memristors as synapses rather than axons: simulations have shown that memristive connections could be used to reproduce spike-time dependent plasticity[6] (the process by which synapses adjust their connection weight to implement Hebbian learning[7]) and even implemented as synapses in evolved spiking networks simulations[8].

Recently, it has been noted that both our and other group's memristors possess a current-spike response to a change in voltage[9]. Thus we thought that memristors ought to be able to replicate neuronal architecture and produce dynamics associated with neurons, such as brainwaves or spike trains.

Our Memristors:

Currently we are interested in a neuromorphic computing and possible appearance of chaotic behaviour. Therefore we shall do a study on the effects of interacting memristors using real world memristors. Our memristors are titanium dioxide sol-gel memristors based on [10] as described in [11,12]. Our Al-TiO_2-Al memristors come in two types:
A. curved memristors which are non-linear over their whole voltage range and
B: triangular memristors which have an Ohmic low resistance state.

The curved memristors are thought to operate by a bulk mechanism and are closer to Chua's theoretical memristors. The triangular memristors are thought to to operate via a filamentary mechanism and are memristive systems where the second state variable is the connection state of the filament[13].

By using real world memristors we are able to make use of the memristor's actual behaviour, whereas theoretical models of the memristor are less useful in this regard as the utilisational behaviour can be abstracted out or the utility may arise from erroneous theoretical assumptions rather than the memristors true behaviour.

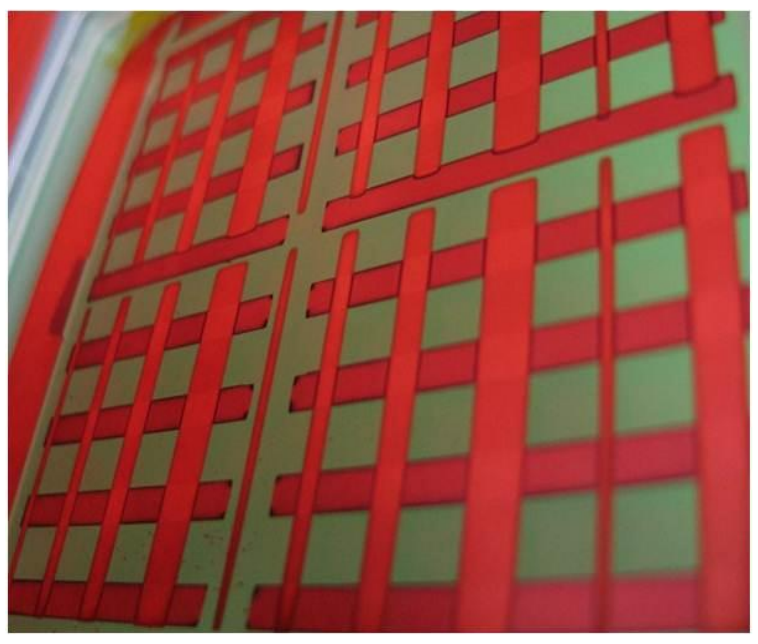

Image of uncut memristors

Methodology:

All experiments were performed with a Keithley 2400 Sourcemeter.
For the I-t curves, the memristor circuits were taken to +0.4V for 1000 timesteps or 1.06s, the voltage source was then switched the 0V and data gathered for a further 100 timesteps.
For the slow I-V test, a sinusoidal voltage of 1600 timesteps of 2s was used to see how the system would response to a slow change. Voltages were kept very low to avoid the creation of filaments via Joule heating which would lead to filamentary memristors switching into lower resistance states.

Single Memristor Circuit Behaviour

The current response of a typical memristor to constant voltage is given in **figure 1**. For this experiment the memristor was taken to the test voltage at 0 seconds and the current recorded as the memristor 'equilibrated'. This was done for two voltages, +1V and -1V. There is assymmetry in the spike responses as the memristors are asymmetric. When voltage is changed we expect a current spike, as this has been seen in all our tests[9] and this is the D.C. action of memristors (forthcoming paper).

For the long time experiments shown later in this paper, the single memristor response is shown in **figure 2**. The spike from the original voltage switch occurs at the start, and then negative spike at 1000 timesteps that results from the change from +0.4V to 0V can be clearly seen.

The signal from the middle section is blown up in **figure 3** to show the quality of the noise; there are no oscillations or large spikes (the spike at the end is the switching spike of the voltage source being turned off).

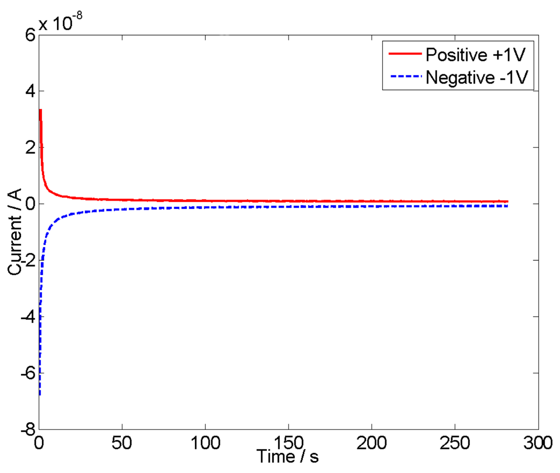

Figure 1.

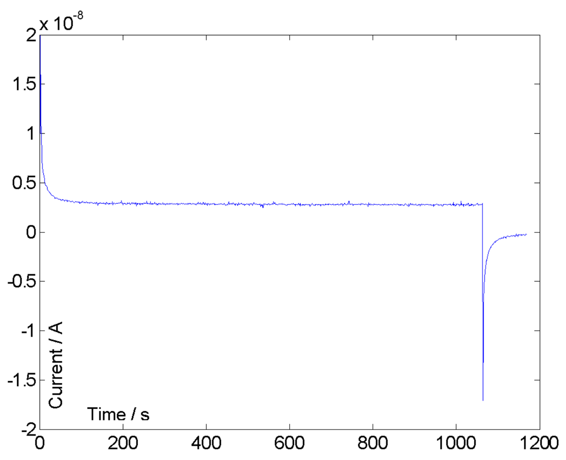

Figure 2.

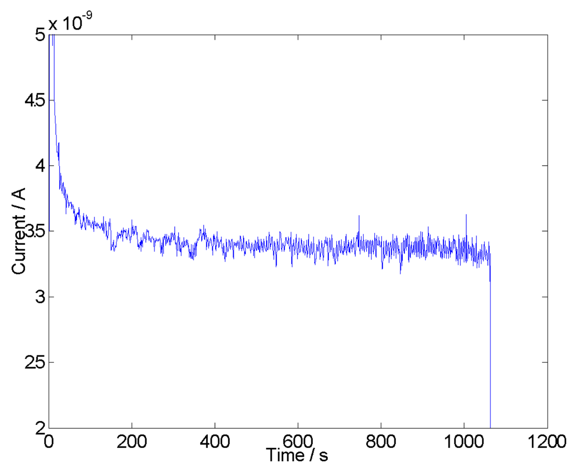

Figure 3.

Three Memristor Circuit Behaviour

A dynamical system can exhibit chaotic behaviour if it has at least three state variables, so we chose to create a circuit with three memristors, which gives us the following three independant state variables: the current through the circuit and the voltage across (any) two of the memristors.

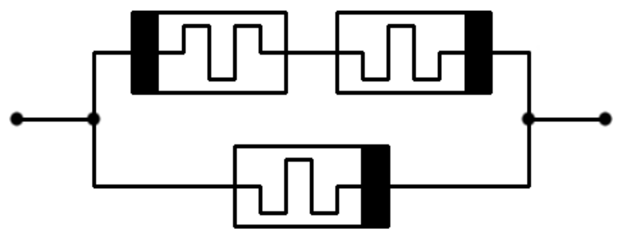

Figure 4.

In order to maximise the compositional complexity of the circuit as shown in **figure 4**, giving us a circuit with two anti-parallel interactions. It was thought that the memristors would spike with the change of voltage and this would cause a change in resistance within a single memristor, which with this circuit set-up would lead to a voltage change across the other memristors and thus further spikes. We used filamentary memristors for this circuit.
Typical results for this circuit are given in **figures 5** and **6**. Comparing this with the expected curve in for one memristor shown in **figure 2**, it shows several differences. The large spike at the start has vanished, as has the one at the end. We see oscillations in the base line, with spontaneous spiking overlaid
over the top. Several runs of this circuit were done to see if there was a repetition in the spiking pattern and thus if the circuits were following an long-term periodic dynamics, this was not the case.

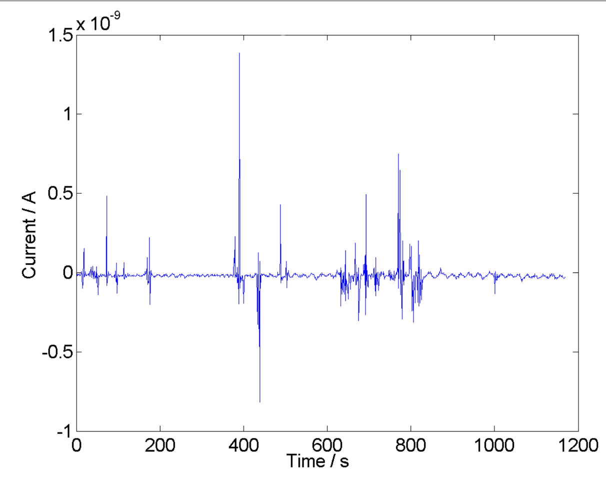

Figure 5.

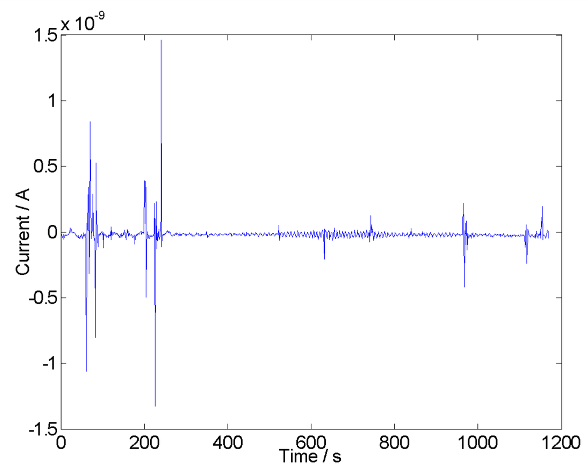

Figure 6.

Two Memristor Circuit Behaviour

To try and understand this, a pair of two memristor circuits which are sub-circuits of the three memristor circuit were made. **Figure 7** shows the series circuit with two memristors wired up with opposite polarity, and the I-t curve is shown in **figure 9**. This has some spikes, faster oscillation but a very low current.
Figure 8 shows two memristors in parallel and the I-t curves are shown in **figure 10**, this has a higher current. These data show that two memristor circuits can produce rich behaviour with spikes and oscillations, however the behaviour is not as rich with two memristors as it is with three

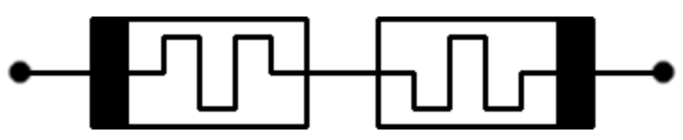

Figure 7.

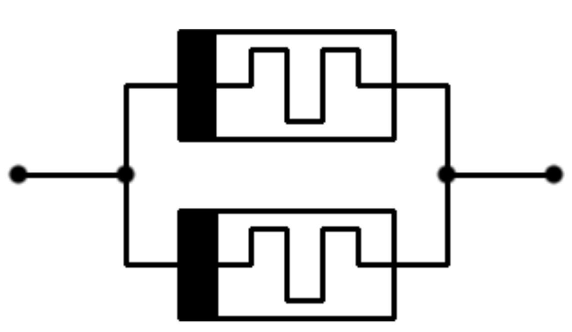

Figure 8.

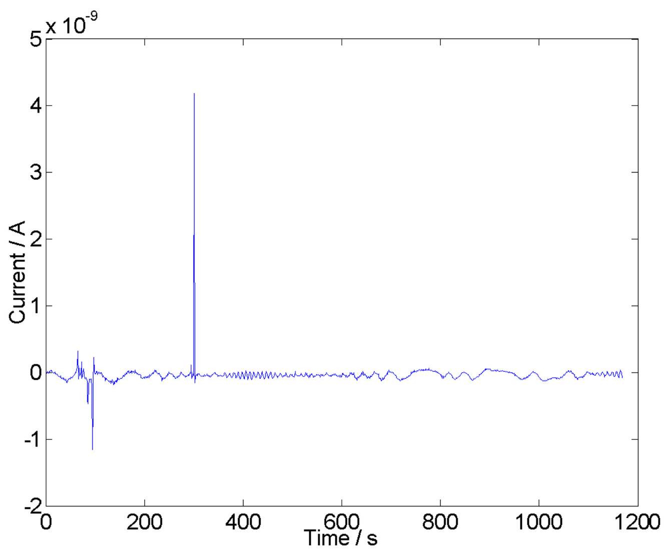

Figure 9.

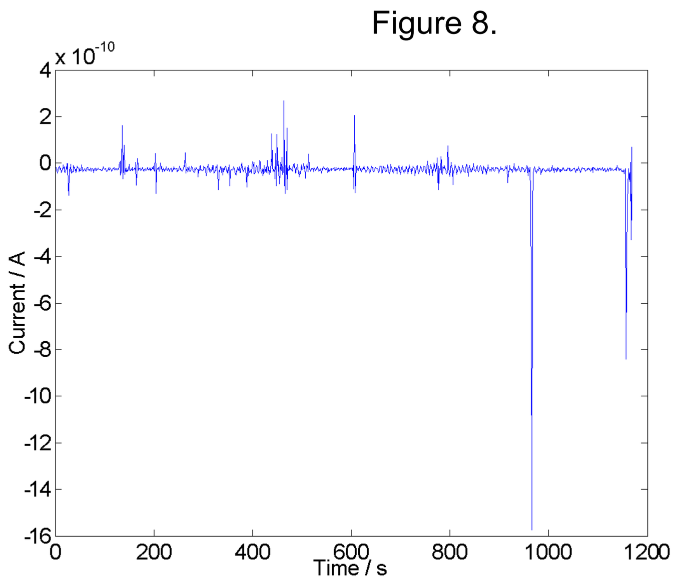

Figure 10.

Discussion

We have shown that three memristors can produce rich behaviour, including brain-wave-like oscillations and spiking events. An interesting question is where has the large spike at the start gone and where have the switching spikes expected from the I-V curve gone. We believe that the energy of the current spike, in fact the current itself, has been 'absorbed' into the memristor network and is the cause of the latter spiking events. We have also shown that when there is either parallel interaction or a polarity dierence between the memristors, there is a higher chance of richer behaviour. From these circuits it is apparent that the circuit fragment of two memristors in antiparallel (i.e. in parallel with opposite polarity) has the highest chance of neuromorphic-like rich dynamics. This is supported by the results reported in the literature and suggests that the theoretical results reported in [14] are due to the fact their Chua circuit possesses two memristors in antiparallel rather than a problem with the model.

The background oscillations are interesting. Although they could be dismissed as sampling noise or background noise, we do not believe this to be the case as they are not seen in the single memristor circuit and are several orders of magnitude above what would be expected on the experimental setup used. They could be some low level emergent phenomena related to the spikes. Instead, we think it's to do with the movement of the boundary, w(t). These `waves' appear similar to that of interacting oscillators, and thus we think its potentially related to the boundary which may be oscillating due to the movement of ions around the dynamic equilibrium point, and it is this behaviour that adds up and interacts in the circuit with more than one memristor in it.

Further Work

This represents preliminary work in this area. Although the dynamics look rich, we need to do further analysis to discover what is the cause of this behavioural richness, quantify it and test whether the trajectory is genuinely chaotic. We are currently undertaking further investigations, both experimental and theoretical, into the mechanism of this behaviour.

References

[1] L. O. Chua. Memristor - the missing circuit element. IEEE Trans. Circuit Theory, 18:507{519, 1971.
[2] D. B. Strukov, G. S. Snider, D. R. Stewart, and R. S. Williams. The missing memristor found. Nature, 453:80{83, 2008.
[3] Leon O. Chua and Sung Mo Kang. Memristive devices and systems. Pro- ceedings of the IEEE, 64:209{223, 1976.
[4] Leon Chua, Valery Sbitnev, and Hyongsuk Kim. Hodgkin-huxley axon is made of memristors. International Journal of Bifurcation and Chaos, 22:1230011 (48pp), 2012.
[5] Leon Chua, Valery Sbitnev, and Hyongsuk Kim. Neurons are poised near the edge of chaos. International Journal of Bifurcation and Chaos, 11:1250098 (49pp), 2012.
[6] Bernabe Linares-Barranco and Teresa Serrano-Gotarredona. Memristance can explain spike-time dependent plasticity in neural synapses. Nature Precedings.
[7] D. Hebb. The Organisation of Behaviour. Wiley, 1949.
[8] D. Howard, E. Gale, L. Bull, B. De Lacy Costello, and A. Adamatzky. Evo- lution of plastic learning in spiking networks via memristive connections. IEEE Transactions on Evolutionary Computation, 16:711{729, 2012.
[9] Ella M Gale, Benjamin de Lacy Costello, and Andy Adamatzky. Observa- tion and characterization of memristor current spikes and their application to neuromorphic computation. In 2012 International Conference on Nu- merical Analysis and Applied Mathematics (ICNAAM 2012), Kos, Greece, Sept 2012.
[10] Nadine Gergel-Hackett, Behrang Hamadani, Barbara Dunlap, John Suehle, Curt Richer, Christina Hacker, and David Gundlach. A exible solution- processed memrister. IEEE Electron Device Letters, 30:706{708, 2009.
[11] Ella Gale, Dave Pearson, Stephen Kitson, Andrew Adamatzky, and Ben de Lacy Costello. Dierent behaviour seen in exible titanium dioxide sol- gel memristors dependent on the choice of electrode material. In Technical Digest of Frontiers in Electronic Materials, pages 577{578. Nature Confer- ence, Wiley-VCH, June 2012.
[12] S. Kitson A. Adamatzky B. de Lacy Costello E. Gale, D. Pearson. Alu- minium electrodes effect the operation of titanium oxide sol-gel memristors. arXiv:1106.6293v1, 2011.
[13] Ella M Gale, Benjamin de Lacy Costello, and Andy Adamatzky. Filamen- tary extension of the Mem-Con theory of memristance and its application to titanium dioxide Sol-Gel memristors. In 2012 IEEE International Con- ference on Electronics Design, Systems and Applications (ICEDSA 2012), Kuala Lumpur, Malaysia, November 2012.
[14] Arturo Buscarino, Luigi Fortuna, Mattia Frasca, and Lucia Valentina Gambuzza. A chaotic circuit based on hewlett-packard memristor. Chaos, 22:023136, 2012.