An Artificial Bio-Synapse Based on Ag/a-Si:Ag/a-Si/X Memristors With Different Bottom Electrode X

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Abstract. In this paper, memristors with three different bottom electrodes as p-Si, Ag and ITO have been fabricated successfully. The memristor is designed as Ag/a-Si:Ag/a-Si/X, in which X refers to p-Si, Ag or ITO. The dielectric layers of a-Si:Ag/a-Si are fabricated by co-sputtering and the final device is completed by standard MEMS processes. The I-V curves, voltage sweeps and response currents, short-term memory (STM) to long-term memory (LTM), and the stability of memristors are studied extensively to mimic the synaptic behavior. It is indicated that the bottom electrode of the Ag/a-Si:Ag/a-Si/X memristors has an obviously influence on the performance of the decivce, and it is suggested that an optimized structural design is needed when a memristive layer is already chosen.

1. Introduction

For the past few years, memristor has been paid much attention as a promising candidate to emulate synaptic functions in bio-inspired neuromorphic systems [1, 2], and memristor based on a-Si and metal doping is well studied owing to its simple structure similarity with bio-synapse [3], gradually changing conductance [4], compatibility with traditional CMOS processes and also the potential for high integration [5]. Memristor based on metal doping a-Si has an application in mimicking biological synapse due to its special working principle, and the gradually changing conductance of memristor can mimic the change of synaptic weight. In a biological synapse, the pre-synapse activates or inhibits the release of neurotransmitters to the post-synapse [6], which increases or decreases the weight of the synapse. Similar to the bio-synapse, the conductance of memristor based on a-Si:Ag/a-Si two-layer dielectric thin film can be changed by Ag+ moving in the dielectric layer [7], which can vividly mimic the dynamic mechanism of bio-synapse. The function of an artificial bio-synapse based on the memristor consist of electrode/a-Si:Ag/a-Si/electrode was demonstrated and shown good performance to mimic the function of bio-synapse [1], but the effect of electrode of this memristor was not mentioned.

In this paper, memristors with three different bottom electrodes as p-Si, Ag and ITO are studied, respectively. The memristor is designed as Ag/a-Si:Ag/a-Si/X, in which X refers to p-Si, Ag or ITO. The dielectric layers of a-Si:Ag/a-Si are fabricated by co-sputtering method and the final device is completed by standard MEMS processes. The I-V curves, voltage sweeps and response currents, short-term memory (STM) to long-term memory (LTM), and the stability of memristors are studied extensively to mimic the synaptic behavior.

2. Experimental Details

The a-Si:Ag/a-Si dielectric layers were deposited on ITO, Ag and p-Si substrates by RF magnetron sputtering, respectively. The PVD chamber was pumped to a base pressure of 7×10-4 Pa and the substrates were heated to 200℃ before deposition. The RF power was set to 200 W. Argon (Ar) flow served as working gas was kept at 250 sccm to keep the chamber pressure in 0.5 Pa. To introduce Ag atoms into the dielectric layer, several Ag chips (99.99 %) were fixed on the Si target (99.999 %). After a-Si:Ag/a-Si bi-layer thin films were deposited, photoetching was used to form the patterns of the top electrode first, and then Ag target (99.99 %) was used to deposite Ag film by DC magnetron sputtering in the condition of 0.5 Pa gas pressure and a DC power of 200 W. The memristors were finally completed after a metal lift-off technique. All electric measurements were performed based on a Keithley 2636B apparatus and a probe system. During measuring, the voltage was applied on top Ag electrode and the bottom p-Si, Ag, or ITO electrode was grounded. In the synaptic function testing of the three different memristors, the response currents were taken as the post-synaptic currents.

3. Results and discussion

The I-V property of the memristor is often used to mimic the performance of a bio-synapse [8]. A biological synapse has many typical functions such as short-term plasticity behaviors (STP and STD) [9], long-term plasticity behaviors (LTP and LTD) [10], short-term memory (STM) to long-term memory (LTM) [11], spike-timing-dependent plasticity (STDP) [12], etc. We have carried out voltage sweeps and the related response currents to mimic the synaptic memory and forgetting function, and the synaptic behaviours can be converted from short-term memory (STM) to long-term memory (LTM) under repeated identical pulse stimuli.

3.1. I-V measurment

Figure 1(a) shows the structure of our artificial bio-synapse based on Ag/a-Si/a-Si:Ag/X memristor and a schematic illustration of a biological synapse. It is known that the a-Si:Ag dielectric thin film has a higher conductivity than a-Si thin film [13]. Inside the memristor, there is a conductive front interface between the two dielectric films [1], which will move from a-Si:Ag layer to a-Si layer (or from a-Si layer to a-Si:Ag layer) when a positive or a negative bias is applied, and the Ag atoms in a-Si:Ag will be oxidized to Ag cations (Ag+) and moved in the direction of the electric field, resulting in an obvious change in the volume fraction of whole a-Si:Ag/a-Si dielectric layer, thus increasing or decreasing the conductivity of the dielectric layer (i.e. the a-Si:Ag/a-Si bi-layer). The memristive behaviours mentioned above can be used to emulate the working principle of bio-synapse, i.e. the concentration of metal cation (e.g. Ca2+, K+) in bio-synapse will influence the synapse weight by releasing more or less neurotransmitters [12] when the pre-synapses send signals of excitement or inhibition to the post-synapses. Figure 1(b), (c) and (d) demonstrate the I-V behaviors of the memristors with p-Si, Ag and ITO as the bottom electrode, respectively. When five consecutive positive/negative scanning voltages are applied on these three devices, the conductance of the devices should be increased/decreased continuously. However, some different behaviors can be found in these I-V curves. When the range of voltage scan is 0~5 V, the memristor with p-Si bottom electrode represents a current variation in the range of 0~7 mA, and the conductance of the device is gradually increased/decreased and the increased/decreased current curve shows the same properties as expected, as shown in Fig 1(b), and this can be used to mimic the remember-forget behavior of a synapse. When the same scanning voltage is applied on the memristor with Ag bottom electrode, the device has a working current in the range of 0~350 mA, which is much higher than that of the other two devices. Furthermore, the gradually increased/decreased conductance can not be found in this device, whether the voltage sweep is positive or negative, and the conductance of the device is almost constant. At the same time, there is no characteristic regression curve, as shown in Fig 1(c). When the same scanning voltage is applied on the memristor with ITO bottom electrode, the device has an even lower working current in the range of 0~1.6 mA. When a positive scanning voltage is applied, the I-V curve is the exact opposite of what is expected, which means that the conductance of the device decreases, rather than increases, under a positive bias. When a negative scanning voltage is applied, there is no obviously conductance direction variation, as shown in Fig 1(d). It is easy to find that the memristor with different bottom electrode has an adaptive working bias. In the case of memristor using p-Si as bottom electrode, the bottom electrode itself is an inert one, has no effect on the dielectric layer. In the case of memristor using Ag as bottom electrode, when an electric field is build up in the device, some Ag atoms in the bottom electrode will be oxidized to Ag cations (Ag+). At this time, when the memristor is under a negative bias, Ag+ will be moved into dielectric layer from the bottom electrode and greatly increase the conductivity of the dielectric layer. This is why this device (Ag as the bottom electrode) has a higher working current than others. In the case of memristor using ITO as bottom electrode, when an electric field is set up in the device, some O2- will be moved into dielectric layer from the bottom electrode and decrease the conductivity of the dielectric layer. This case is quite different from the other two cases. On the one side, the moving of Ag+ will increase the conductivity of dielectric layer, but on the other side, the moving of O2- will decrease the conductivity of dielectric layer, and as a result, the final conductivity of the whole memristive layer is obviously decreased.

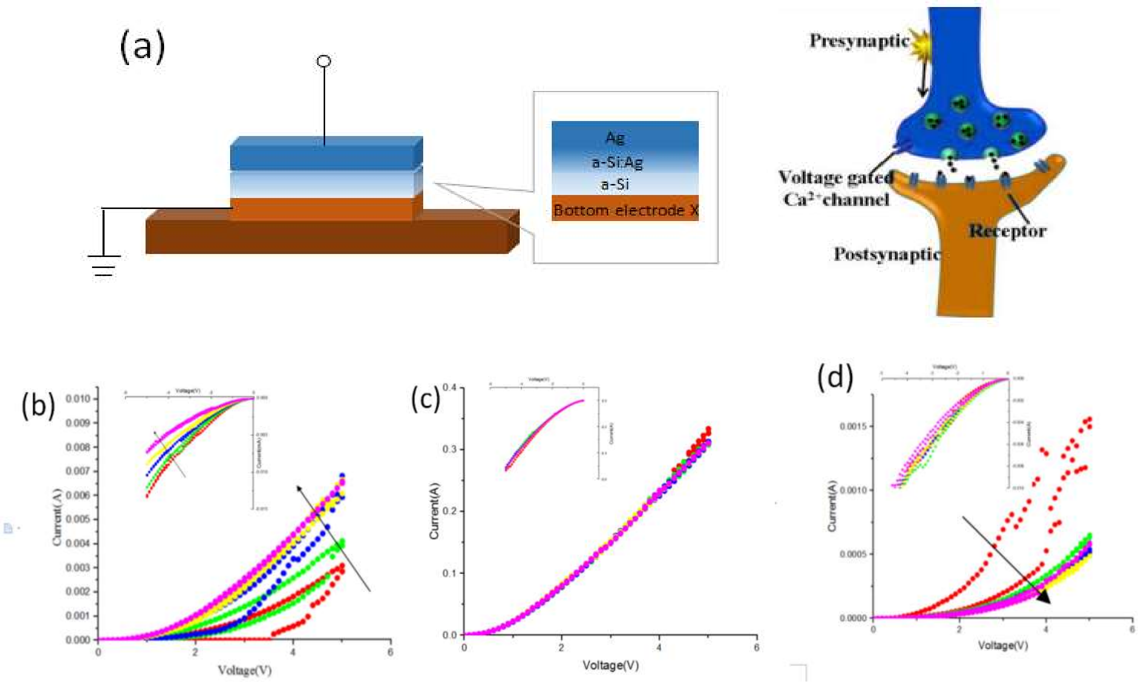

Figure 1. The structure of Ag/a-Si:Ag/a-Si/X memristor and a schematic illustration of a biological synapse (a), with I-V curves of memristors using p-Si (b), Ag (c), or ITO (d) as bottom electrode under 5 consecutive voltage sweeps from 0 V to 5 V. The three insets are 5 consecutive voltage sweeps from 0 V to -5 V.

3.2. STM to LTM Transition

In a biological system, STM generally holds a shorter time compared with the LTM [11]. According to the forgetting and remembering behaviors in brain, the STM can transform into the LTM through rehearsal process. Under a preliminary stimulus, little Ag+ migrates into the a-Si layer from the a-Si:Ag layer and the Ag atoms tend to decay at the initial state spontaneously, but later more Ag+ will migrate into the a-Si layer under repeated stimulations, just like the training process in a biological system. Figure 2(a) shows the same positive pulses applied to the three memristors, the height of these pulses is

5 V, and the number of pulses is 9. In Figure 2, the memristive devices undergo a series of stimulating pulse trains, and the post-synaptic respond current is measured simultaneously. As shown in Figure 2(b) and 2(c), i.e. the bottom electrode is p-Si or Ag, the respond current increases rapidly under 5 V stimulating pulse and then decays to a remained low current state, which is corresponding to the STM behavior in a bio-synapse and the post-synaptic response current has an overall increase under the former seven stimulating pulses. In the artificial synapse using p-Si as the bottom electrode of the memristor, the post-synaptic response current is up to 0.4 mA (Figure 2(b)), however, in the artificial synapse using Ag as the bottom electrode of the memristor, the post-synaptic response current is up to 20 mA (Figure 2(c)), resulting from the fact that Ag+ is moved from the bottom electrode into the dielectric layer. It can be seen from Figure 2(b) and Figure 2(c) that the response current difference of Ag/a-Si:Ag/a-Si/p-Si is much larger than that of Ag/a-Si:Ag/a-Si/Ag, the former is about four times larger than the latter. This comparison suggests that the former synapse has a better memory performance. However, one can not find any synaptic characteristics in Ag/a-Si:Ag/a-Si/ITO from Figure 2(d), in which no obvious regularity in the change of response current can be observed when using ITO as the bottom electrode. The performance is somewhat chaotic, which might be due to the alternating/competing effect of Ag+ and O2- on the final conductivity of the whole dielectric layer.

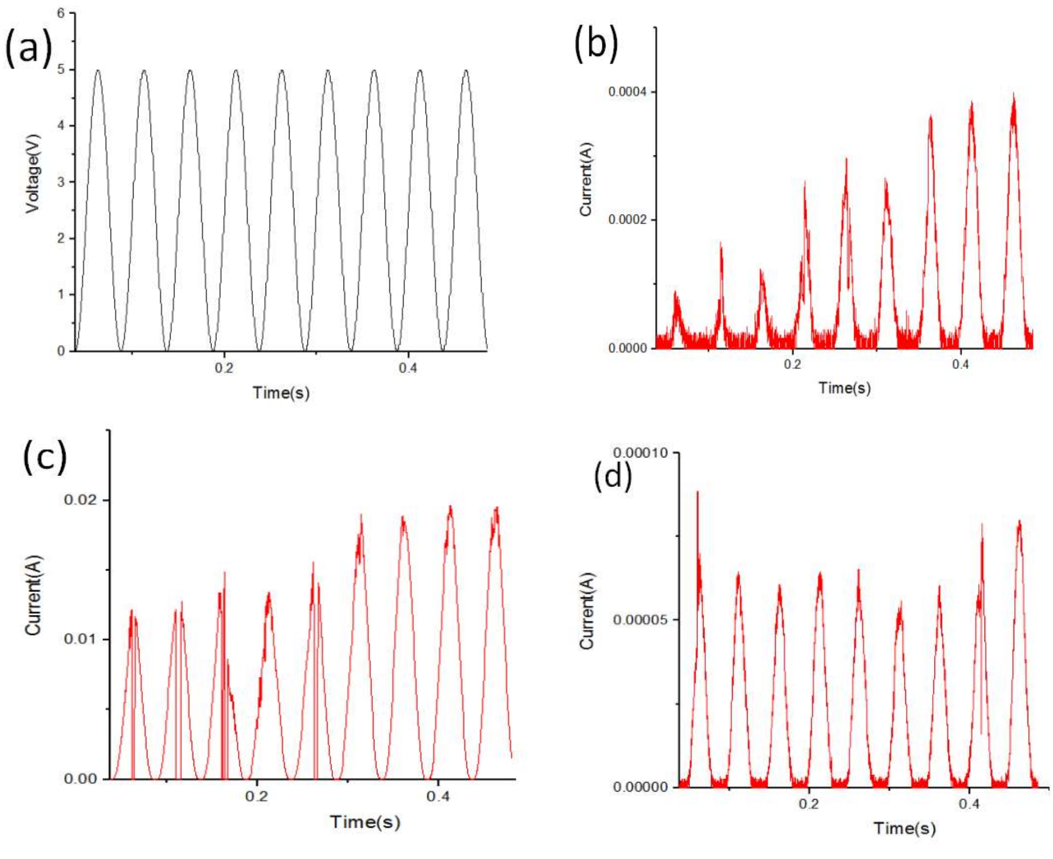

Figure 2. The pulses applied to memristors (a) and the response current of memristor using p-Si (b), Ag (c), or ITO (d) as bottom electrode under the same pulses.

3.3. Stability of the bio-synapse

Figure 3 shows the I-V curves of memristor with p-Si, Ag, or ITO bottom electrode respectively after 100 cycles of voltage sweeps, and the figure inserted shows the I-V curves of memristor after 500 cycles of voltage sweeps. As shown in figure 3(a), after 100 and 500 cycles of voltage sweeps, memristor with p-Si as bottom electrode has a similar curve compared to the initial voltage sweep (shown in figure 1(b)), the changes in conductance with positive or negative voltages are still similar to those of a synapse, which suggests that this memristor still has synaptic function of remember-forget. Figure 3(b) shows that memristor with Ag as bottom electrode has some synaptic function after 100 cycles of voltage sweeps, however the I-V curve is more like a resistance rather than a memristor after 500 cycles of voltage sweeps, this may be caused by too much silver entering the dielectric layer. Figure 3(c) shows that memristor with ITO as bottom electrode has a curve similar to that of a synapse device but the changes in conductance with positive or negative voltages are contrary to those of a synapse after 100 cycles of voltage sweeps, however, this situation is changed after 500 cycles of voltage sweeps, memristor shows the similar curve to a synapse, at this time, the influence of Ag+ on the conductivity of dielectric layer is dominant.

These three figures suggest that memristor with p-Si as bottom electrode is stable and has a long life, but memristor with Ag as bottom electrode is unstable, and memristor with ITO as bottom electrode needs to work for some time before it shows normal memory performance.

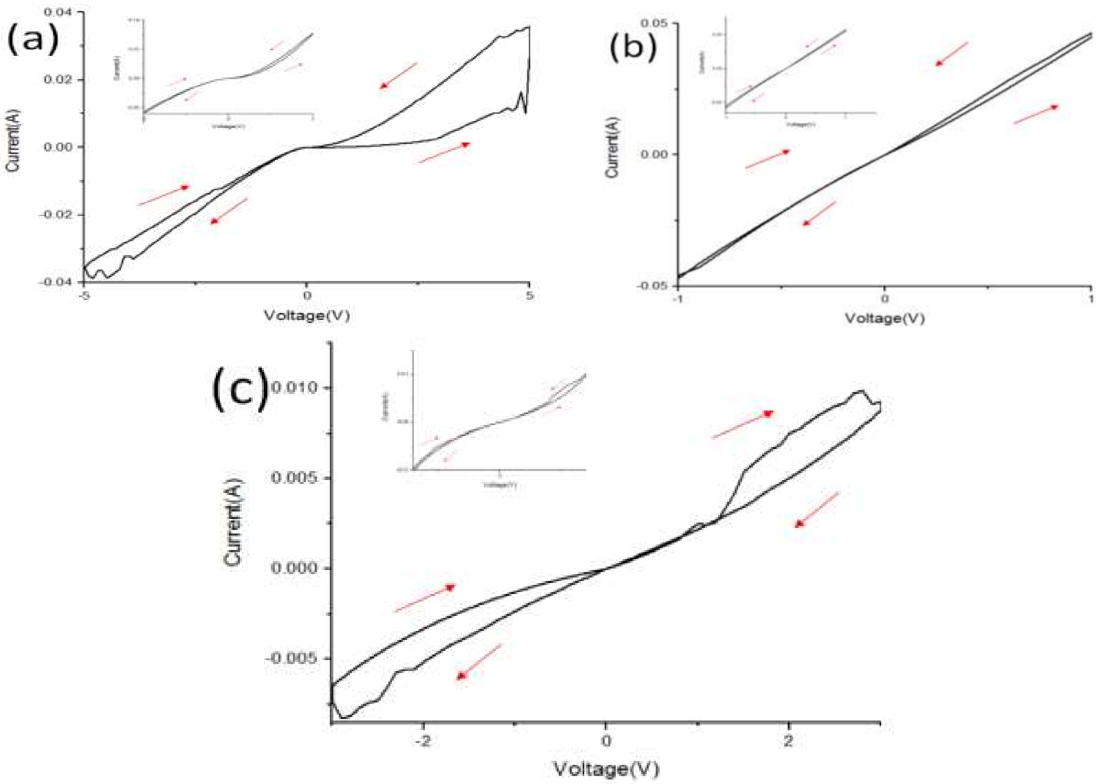

Figure 3. The I-V curves of memristor with p-Si (a), Ag (b), or ITO (c) bottom electrode after 100 cycles voltage sweeps. Inset: The I-V curves of memristor after 500 cycles.

4. Conclusion

In summary, memristors with different bottom electrodes have its own specific structures and show variable performance. Memristor with p-Si as bottom electrode can be used to mimic bio-synapse, and has a relatively stable property such as STM transform into the LTM. Memristor with Ag as bottom electrode has a larger working conductance, which can also be used to mimic bio-synapse in some circumstance when a large read current is required. But this memristor is not so stable concerning about its voltage sweeping time. Memristor with ITO as bottom electrode shows a stable performance but presents an abnormal bio-synaptic behavior at early hundreds of voltage sweeps. It is indicated that the bottom electrode of a memristor structured as Ag/a-Si:Ag/a-Si/X has an obviously influence on the performance of the decivce, and it is suggested that an optimized structural design is needed when a memristive layer is already chosen.

Acknowledgments
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