Biological synapse mimicked in an inorganic Cu_2S gap-type atomic switch

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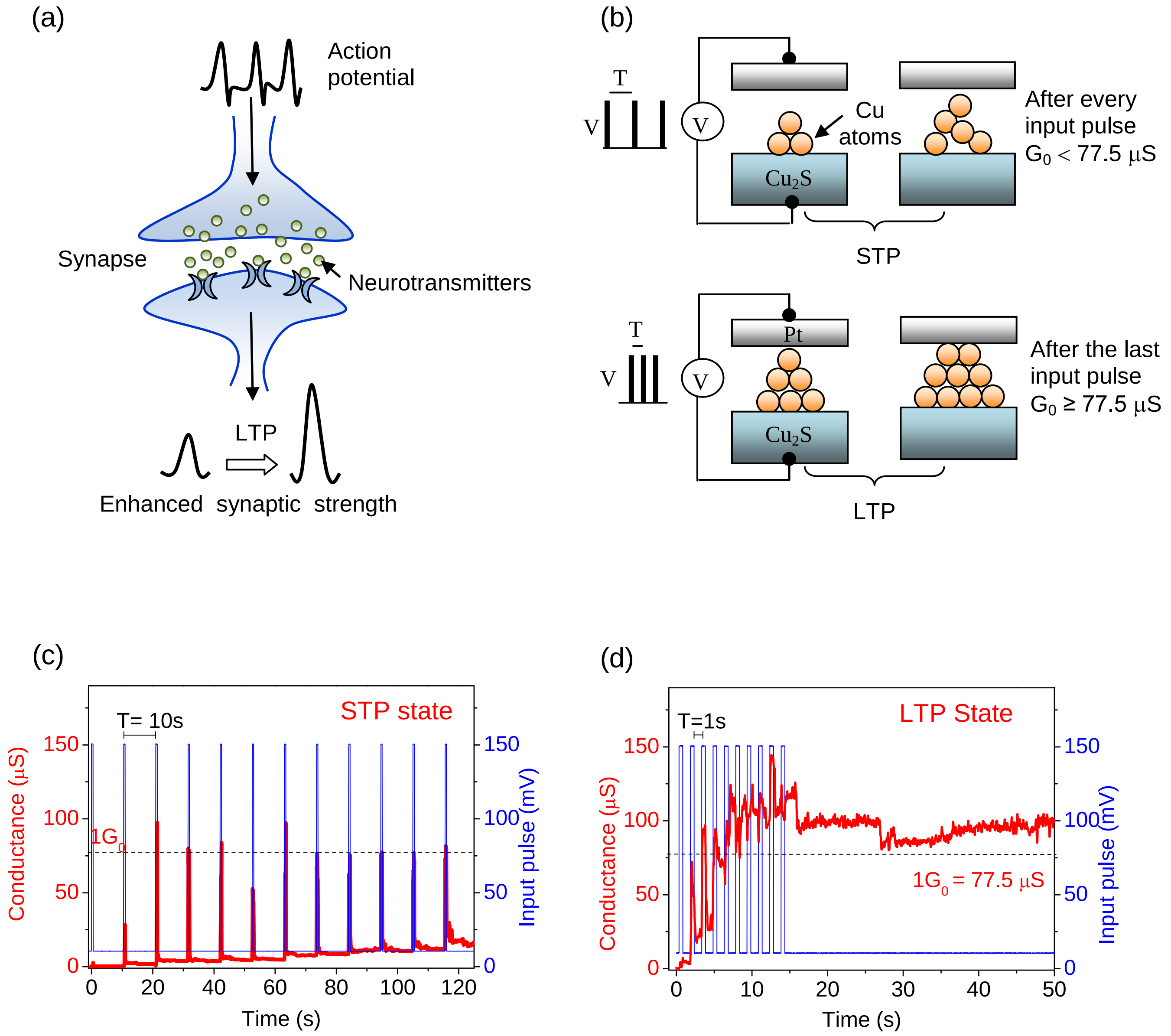
A gap-type atomic switch[1], which operates by formation and annihilation of Cu atomic bridge across a nanogap between a Cu_2S solid-electrolyte electrode and an inert metal electrode (Pt), exhibits interesting characteristics with analogies to an individual biological synapse. Application of input voltage pulses (stimuli) causes precipitation of Cu atoms from the Cu_2S electrode due to a solid electrochemical reaction, resulting in the formation of the Cu atomic bridge. Consequently, the conductance between the Cu_2S and Pt electrodes increases. The switch shows two types of conductance states: first, a temporary increase in conductance followed by spontaneous decay over time achieved by input stimuli at a lower repetition rate, and second, a persistent enhancement of conductance achieved by a frequent input stimuli repetition. These two states are analogous to the short-term plasticity (STP) and long-term potentiation (LTP) states, respectively, in a biological synapse wherein a persistent increase in the synaptic strength is achieved following a higher repetition stimulation by action potentials (Figure (a)).

Similar behavior has also been observed in an Ag_2S gap-type atomic switch recently[2,3]. We explain these conductance states in terms of the atomic bridge formation and its stability. In our inorganic STP state, the precipitated Cu atoms do not form a complete bridge (Figure (b)) and the higher-conductance of approximately one quantized channel ($1G_0 = 2e^2/h = 77.5\ \mu S$) is not maintained after each input pulse (Figure (c)). On the other hand, in the LTP state, a complete and robust atomic bridge is formed (Figure (b)) and a conductance higher than 77.5 μS is maintained after the last input pulse (Figure (d)). Changes in conductance, including transition between these two states, depend on temperature and strength of the input stimuli. For instance, by increasing temperature and the pulse amplitude and width, the number of input pulses required to attain a LTP state reduces drastically. Compared with Ag_2S, the Cu_2S system needs input pulses of higher amplitude because of its higher activation energy for the chemical reaction. However, both of the inorganic synapses achieve dynamic memorization in a single device without the need of external preprogramming. In addition, the variation depending on the materials will enable us to develop more complex circuit elements which may lead to the construction of artificial neural networks for computing applications.

References

[1] K. Terabe, T. Hasegawa, T. Nakayama, and M. Aono, Nature, **433** (2005), 47.
[2] T. Hasegawa, T. Ohno, K. Terabe, T. Tsuruoka, T. Nakayama, J. K. Gimzewski, and M. Aono, Adv. Mater. **22** (2010),1.
[3] T. Ohno, T. Hasegawa, T. Tsuruoka, K. Terabe, J. K. Gimzewski, and M. Aono, Nature Materials, **10** (2011), 591.



Figures. (a) In a biological synapse, the release of neurotransmitters is caused by the arrival of action potentials and then a signal is transmitted as a synaptic potential. Frequent stimulation causes long-term enhancement in the synaptic strength. (b) Schematic of a Cu_2S inorganic synapse showing short-term plasticity (STP) and long-term potentiation (LTP) states depending on the input-pulse repetition time (T).When the precipitated Cu atoms do not form a complete bridge between the Cu_2S and Pt electrodes, the inorganic synapse works as STP. After a complete and robust atomic bridge is formed, it works as LTP. (c-d) Change in the conductance of the inorganic synapse when the input pulses (amplitude (V) = 150 mV, width = 500ms) were applied with intervals of T =10 s (c) and 1 s (d). The conductance of the inorganic synapse with a single atomic contact is given by $G_0=2e^2/h=77.5$ μS.