Synaptic characteristics of the atomic switch

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More than ten years ago, some of the present authors (Aono, Hasegawa and Terabe) and co-workers developed the atomic switch [1, 2]. The atomic switch is generally known as such nanoscale switching devices that make ON/OFF switching by the growth and shrinkage of a conduction path composed of metal atoms (in contrast with other nanoscale switching devices collectively called the resistive switch in which a conduction path is formed by anion [e.g. oxygen ion] vacancies, etc.). Actually, the atomic switch has more interesting functionalities depending on its structure and constituent materials (see Fig. 1). In this paper, after reviewing the general characteristics of the atomic switch briefly, we would like to concentrate on the discussion of the synaptic characteristics of the atomic switch.

![Figure 1: Various types of the atomic switch, which have different structures and constituent materials.](image)

The atomic switch was first developed as a nanoscale, two-terminal, nonvolatile switch with a nanoscale vacuum gap between a solid-electrolyte (Ag₂S) electrode and a simple-metal counter electrode, i.e. a gap-type atomic switch [1, 2]; if necessary, a volatile atomic switch can be made [3]. It has been found later that the vacuum gap can be filled with soft organic molecules [4] and if the molecules are photoconductive, a photosensitive atomic switch can be made, where ON/OFF switching is controlled by photons [4]. The switching mechanism of the gap-type atomic switch has been studied in detail [5-7].

Soon after the development of the gap-type atomic switch, we developed a
gapless-type atomic switch without a gap between a solid-electrolyte electrode (Cu$_2$S was used) and a simple-metal counter electrode [8-11]; this gapless-type atomic switch is advantageous for practical application. We have also found that the solid electrolyte in the gapless-type atomic switch can be a polymer-based electrolyte (e.g. poly-ethylene + AgClO$_4$) [12], suggesting that a flexible two-dimensional atomic switch array can be fabricated. Moreover, it has been found that the electrolyte in the gapless-type atomic switch can be replaced by a metal oxide (e.g. Ta$_2$O$_5$) [13-17]; the metal oxide is not a solid electrolyte but works as an ion transport layer. The switching mechanism of this ion-transport-layer atomic switch has been studied in detail [18-21].

We have succeeded to develop three-terminal atomic switches (transistors) using a solid electrolyte (Cu$_2$S) [22, 23] or an ion-transport layer (Ta$_2$O$_5$) [24, 25]. Interestingly, an atomic transistor using Ta$_2$O$_5$ can be operated in either volatile or non-volatile modes by simply controlling applied voltage [24].

Interestingly, we have revealed that the two-terminal gap-type atomic switch exhibits learning ability [26, 27]; namely, the conductivity of the switch can have intermediate values between the OFF and ON conductivities, depending on the history of input signals. More interestingly, the atomic switch shows interesting characteristics similar to a synapse in neural network [28-30]; such characteristics are also observed in a certain gapless-type atomic switch [31]. On the basis of these results, we have been developing neuromorphic circuits made of atomic switches [28, 31, 32]. These studies have been partially reviewed in Refs. 33-37.

Remarkable results related to the neuromorphic circuits constructed by atomic switches are discussed in detail in this paper.