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Emulating the Ebbinghaus forgetting curve of the human brain with a NiO-based memristor

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The well-known Ebbinghaus forgetting curve, which describes how information is forgotten over time, can be emulated using a NiO-based memristor with conductance that decreases with time after the application of electrical pulses. Here, the conductance is analogous to the memory state, while each electrical pulse represents a memory stimulation or learning event. The decrease in the conductance with time depends on the stimulation parameters, including pulse height and width and the number of pulses, which emulates memory loss behavior well in that the time taken for the memory to be lost depends on how the information is learned.
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The well-known Ebbinghaus forgetting curve illustrates the way in which information is forgotten over time by the human brain. The curve was formulated in 1885 by Hermann Ebbinghaus.[1] Ebbinghaus found that initial information is often lost very quickly after it is initially learned, and factors such as the way in which the information is learned and how frequently the information is reviewed play important roles in the rate at which these memories are lost. The Ebbinghaus forgetting curve is historically described by the equation $R = \exp(-t/S)$, where R is the retention of memory, t is time, and S is the relative strength of the memory. A more quantitative expression for the memory loss is given by[2]

$$P = \exp[-(t/\tau)^{\beta}], \tag{1}$$

where P is the probability of recall, t is time, τ is the characteristic relaxation time, and β is an index that ranges from 0 to 1.

It has been reported in the literature that memristors have the potential to emulate some aspects of the behavior of the human brain, such as its self-learning ability[3,4] and synapse-like functions.[5–9] Recently, Ohno *et al.* reported the discovery of the Ag_2S inorganic synapse.[8] They showed that this inorganic synapse goes beyond simply mimicking synaptic biological behavior and is also useful in psychology for implementation of the Ebbinghaus forgetting curve. They observed that the decay of the conductance of the inorganic synapse in the short-term memory (STM) mode is surprisingly similar to that of the forgetting curve. Chang *et al.* experimentally showed that retention loss in a WO_x-based memristor resembles memory loss in biological systems.[9] More recently, Yang *et al.* demonstrated that the gradually changing volatile and nonvolatile resistance states in a WO_{3-x}-based nanoionic device can be used to mimic the forgetting processes of the human brain for STM and long-term memory (LTM), respectively.[10] In our previous work, forgetting-like behavior was observed in a NiO-based resistive switching device.[11]

In this work, we show that the forgetting curve can be emulated using a NiO-based memristor with conductance that decreases with time after stimulation. The decrease in conductance is governed by the expression given in Eq. (1), which suggests that this conductance decay behavior is analogous to memory loss in the human brain. The decrease in conductance also depends on the stimulation parameters, which well emulates human memory loss behavior that how quickly memories are lost depends on how the information is learned.

The NiO-based memristor, with a metal-insulator-metal (MIM) structure, was fabricated on a 400 nm-thick SiO_2 film that had been thermally grown on a p-type silicon wafer. The bottom electrode was formed by depositing a 120 nm Ni layer on the SiO_2 film by electron beam evaporation. A NiO thin film with a thickness of ~150 nm was deposited on the Ni layer by radio frequency (13.6 MHz) magnetron sputtering of a NiO target (>99.99% purity) with an Ar flow rate of 75 sccm. The rf power used here was 250 W. Finally, a 150 nm Au/15 nm Ni layer was deposited on the NiO film by electron beam evaporation to form the 200 μm diameter top electrodes. The final thin film structure of the device was formed as $Au/Ni/NiO/Ni/SiO_2$. Electrical characterizations of these structures were carried out with a Keithley-4200 semiconductor characterization system.

The conductance of this NiO-based memristor changes when electrical pulses are applied to it. Figure 1 shows an experiment in which seven pulses with height of 2.5 V, width of 5 ms and a pulse interval of 0.9 s were applied to the device, and the conductance of the device after each pulse was recorded at 30 mV. The conductance was normalized to the initial conductance (G_{init}), which is the conductance value recorded before any electrical pulses were applied. As shown in Fig. 1(b), the device conductance increases immediately after each pulse, which is analogous to the rapid enhancement

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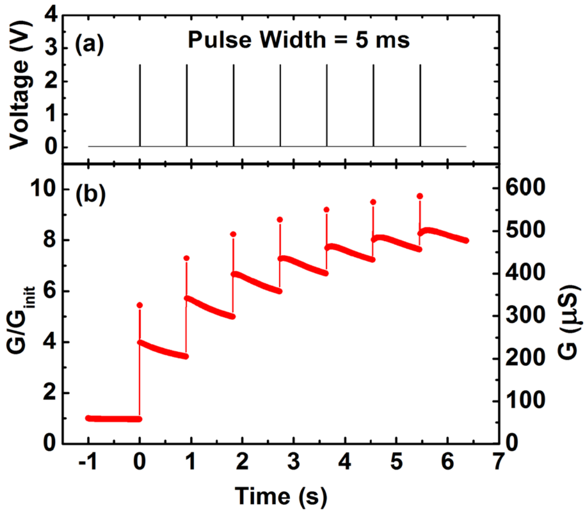

FIG. 1. Enhancement of conductance by repeated pulses with a short pulse interval. (a) Electrical pulses applied to the NiO-based memristor and (b) change in the normalized conductance (left vertical axis) and the conductance (right vertical axis) of the NiO-based memristor with time. The pulse height, pulse width and pulse interval were 2.5 V, 5 ms and 0.9 s, respectively.

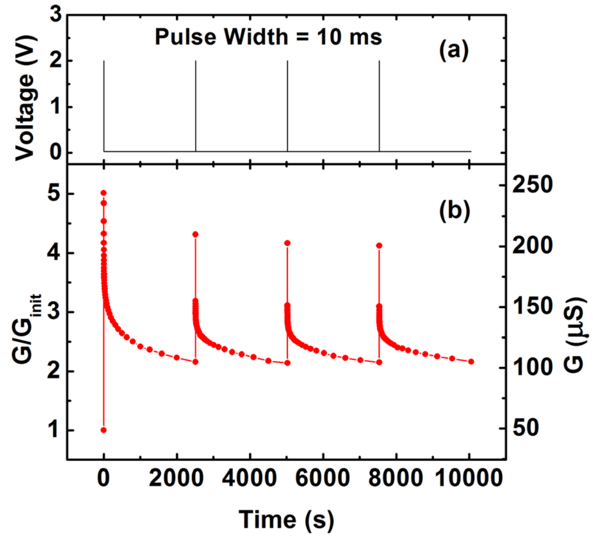

FIG. 2. Conductance in response to repeated pulses with a very long pulse interval. (a) Pulse waveforms applied to the device; and (b) conductance response of the device. The applied pulse height, pulse width and pulse interval were set to 2.0 V, 10 ms and 2513 s, respectively.

of memorization in the STM stage of the human brain that occurs through stimulation/impression. The conductance also decreases during the interval between two consecutive pulses, and this situation is similar to the memory loss that occurs immediately after stimulation. However, the overall conductance increases progressively with the application of the electrical pulses, and this situation is similar to that of memory enhancement in the brain through repeated stimulations. The change in the device conductance can be explained using the conductive filament (CF) model.[12–16] Many local conductive regions formed by oxygen vacancies and/or crystal boundaries exist in the NiO matrix. Electrical pulses can produce both Joule heating effects (e.g., thermally-activated material migration) and field effects (e.g., migration of oxygen ions under the influence of applied electric fields). These effects can make the local conductive regions extend and/or link together to form conductive filaments, resulting in increased conductance. Additionally, the decay of this conductance is attributed to the deformation of these filaments, which could be caused by spontaneous diffusion/migration of the oxygen vacancies[9,10] and/or relaxation of the atoms/ions in the filaments. Heat diffusion during the off-time between the pulses affects both the formation and deformation of the filaments.[15]

The overall device conductance will not increase progressively or even decrease with the electrical pulses if the device is stimulated by pulses at a low rate. Figure 2 shows an experiment in which pulses were applied at a low rate. Four pulses with pulse height, pulse width and pulse interval of 2 V, 10 ms and 2513 s, respectively, were applied to the device, and the conductance was recorded at 30 mV. In Fig. 2, the conductance is shown to decay immediately after each pulse. No progressive increase in the overall conductance can be observed (the overall conductance actually shows a slight decrease), which is unlike the progressive increase in the overall conductance that was shown in Fig. 1(b). The prolonged pulse interval allowed more complete deformation of the conductive filaments, leading to the conductance decay and thus no progressive increase in overall conductance with the application of the pulses. This is similar to the behavior of the human brain, where longer intervals between stimulation events may lead to greater memory loss.

The results shown in Figs. 1 and 2 indicate that, because of the conductance decay, the pulse interval plays an important role in the evolution of the overall conductance. In the experiment shown in Fig. 3, 14 successive pulses at different pulse intervals were applied to each device. The pulse height and pulse width were fixed at 2.5 V and 5 ms, respectively, but the pulse interval was varied from 0.01 s to 10 s. The device conductance was measured at 30 mV immediately after each pulse was applied. Five devices at different locations on the wafer were examined for each pulse interval. The change in the conductance with the number of pulses for various pulse intervals is shown in Fig. 3. As the figure shows, there is a large increase in conductance with the pulse number for pulse intervals of 0.01 s and 0.1 s, while there is only a small

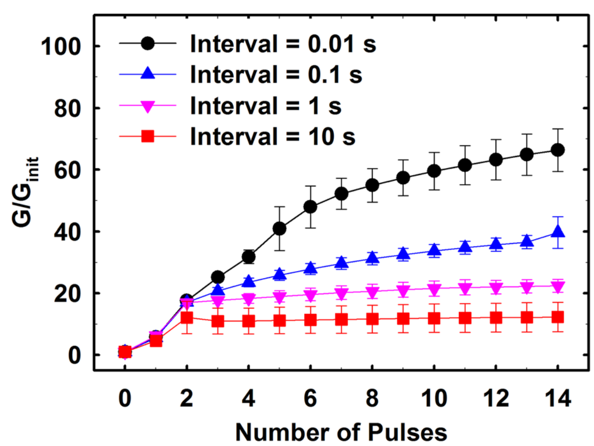

FIG. 3. Normalized conductance of NiO-based memristor as a function of pulse number for various pulse intervals. The pulse height and pulse width were fixed at 2.5 V and 5 ms, respectively, while the pulse interval was varied from 0.01 s to 10 s.

increase in conductance after the second pulse for the pulse interval of 1 s. For the pulse interval of 10 s, there is a significant increase in conductance for the first two pulses, but there is then a small decrease in conductance after the third pulse, and the conductance then remains basically unchanged after any further pulses. The pulse interval plays an important role in the evolution of the conductance, which is similar to the effect in the brain where frequently reviewing the information contributes remarkably to the memorization process.

The conductance decay behavior can be used to simulate memory loss in the human brain. Figure 4(a) shows a forgetting curve for the human brain,[17] which can be described well using Eq. (1) with a characteristic relaxation time τ of 37 s and an index β of 0.31. The following conductance decay experiment was carried out to emulate the forgetting curve. The device was first stimulated with a pulse that was 10 ms wide and 2.0 V high, and the conductance decay with time was then recorded for a period of 10 min. As shown in Fig. 4(b), the experimental results can be described well by the following relaxation equation:

$$\Delta G(t)/\Delta G_0 = \exp[-(t/\tau)^{\beta}], \quad (2)$$

where $\Delta G(t) = G(t) - G_{init}$ and $\Delta G_0 = G_0 - G_{init}$, in which *G(t)* is the conductance at time *t*; G_0 is the conductance measured immediately after stimulation; τ is the characteristic relaxation time of the conductance decay process; and β is an index that ranges from 0 to 1. It should be noted that G_{init} is not the same as G_0. G_{init} is the initial conductance of the device before it has experienced any stimulation, whereas G_0 is the conductance that is measured immediately after stimulation. The fitting shown in Fig. 4(b) yields $\tau = 68$ s and $\beta = 0.37$. These values indicate that the decay of $\Delta G(t)/\Delta G_0$ is analogous to memory loss in the human brain. This means that the memristor can be used to emulate the forgetting curve of the human brain, where $\Delta G(t)/\Delta G_0$ is equivalent to the recall probability *P*.

In the human brain, the rate at which memory is lost depends on the way in which the information was learned. This can also be simulated well with the memristor. Here, the "learning" conditions (i.e., the stimulation conditions) can be varied by varying the pulse number, the pulse voltage and the pulse width. Figure 5 demonstrates the effect of the stimulation number (i.e., the number of pulses) on the decay of $\Delta G(t)/\Delta G_0$. In this experiment, the stimulation strength remained constant, i.e., the pulse width and pulse height were fixed at 10 ms and 2 V, respectively, while the pulse number was varied from 10 to 210 pulses. The device conductance was recorded continuously at 30 mV over the time after stimulation. As shown in Fig. 5(a), the decay of $\Delta G(t)/\Delta G_0$ with time can be described well using Eq. (2) with different pulse numbers, and $\Delta G(t)/\Delta G_0$ decays more slowly for larger pulse numbers. Figure 5(b) shows the dependence of the characteristic time τ and ΔG_0 on the pulse number. Both ΔG_0 and τ increase with the pulse number. The dependence of the decay of $\Delta G(t)/\Delta G_0$ on the pulse number resembles the phenomenon where one can remember something for a longer time if there are more stimuli (e.g., more impressions) at the beginning. The effects of the

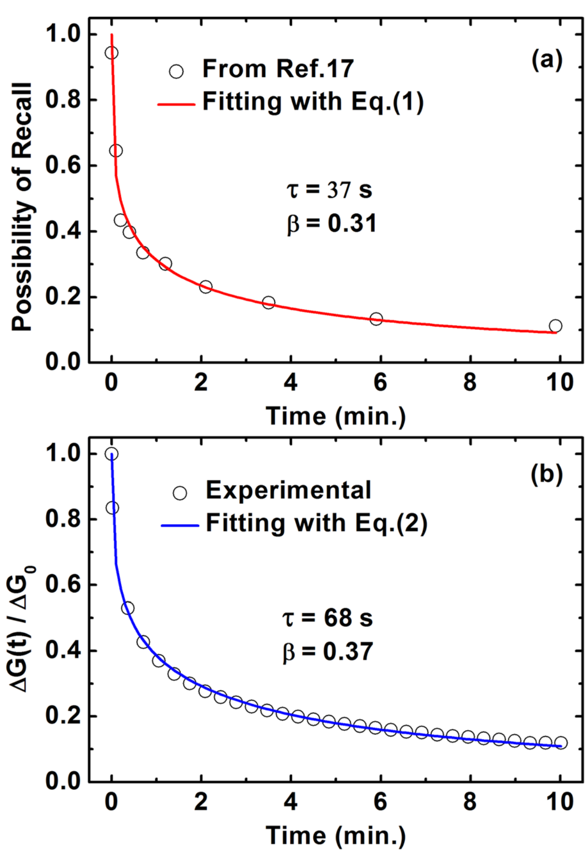

FIG. 4. (a) Forgetting curve of the human brain (see Ref. 17) and (b) decay of $\Delta G(t)/\Delta G_0$ in the NiO-based memristor after stimulation with a 10 ms-wide and 2.0 V-high pulse.

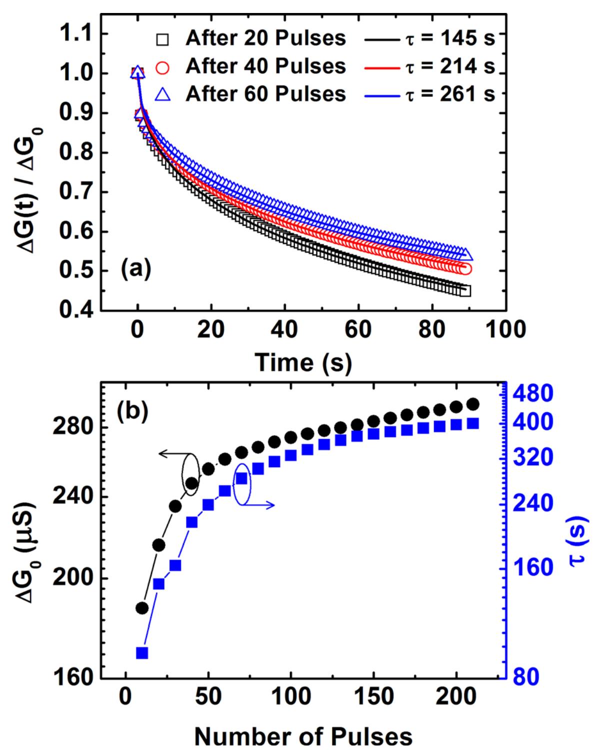

FIG. 5. (a) Decay of $\Delta G(t)/\Delta G_0$ in the NiO-based memristor after stimulation with different numbers of pulses and (b) ΔG_0 and τ (characteristic time) as functions of the pulse number. The pulse height and pulse width were fixed at 2.0 V and 10 ms, respectively.

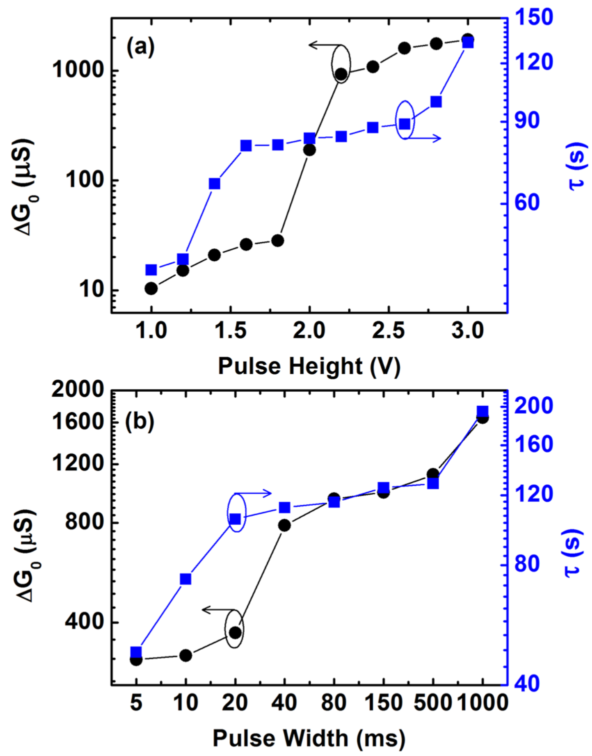

FIG. 6. (a) ΔG_0 and τ as functions of pulse height, and (b) ΔG_0 and τ as functions of pulse width. In (a), 10 consecutive pulses with pulse widths of 10 ms and pulse intervals of 10 ms were applied to the device; in (b), 10 consecutive pulses with pulse heights of 2.0 V and pulse intervals of 10 ms were applied to the device.

stimulation strengths (i.e., the pulse height and pulse width) on the decay of $\Delta G(t)/\Delta G_0$ are demonstrated in Fig. 6. Figure 6(a) shows ΔG_0 and τ as functions of the pulse height. Three regions, i.e., the low ΔG_0 region, the high ΔG_0 region and the intermediate region, can be observed in the curve of ΔG_0 versus pulse height. These regions correspond to the different field dependences of the formation of the filaments, but the detailed mechanism is not yet clear. Figure 6(b) shows the dependence of both ΔG_0 and τ on the pulse width, which is somewhat similar to the dependence of ΔG_0 and τ on the pulse height. As shown in Fig. 6, τ increases with both the pulse height and the pulse width, and thus emulates the behavior of the human brain, where memory loss depends heavily on the stimulation strength.

In conclusion, the forgetting curve can be emulated well using a NiO-based memristor. The conductance decay of the memristor over time is analogous to memory loss in the human brain. The decay of $\Delta G(t)/\Delta G_0$ depends on the stimulation strengths (i.e., the pulse height and the pulse width) and the stimulation number (i.e., the number of applied pulses), which closely emulates the memory loss behavior where the rate at which memory is lost depends heavily on the way in which the information is learned.

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