Electrode material dependence of resistance change behavior in Ta$_2$O$_5$ resistive analog neuromorphic device

Hisashi Shima, Makoto Takahashi, Yasuhsia Naitoh, Hiroyuki Akinaga

Abstract—In a human brain, our closest and very low-power information processor, one neuron transmits electrical signals depending on the electrical stimulation from other neurons. Therefore, it can be regarded as the multi-input one-output system that is the same as an elementary perceptron in the pattern recognition system. In analogy with the actual neurons whose coupling strength varies on a moment-to-moment basis, a flexible control of the weight for each individual input signal is required in order to realize the correct recognition. The analog change of the resistance values observed in the resistance change device is quite suitable for such application. In this contribution we successfully demonstrate the high-speed analog resistance change in the TiN/TaO$_x$/Ta$_2$O$_5$/TiN resistive analog neuromorphic device (RAND). An introduction of the TiN electrode smoothed the discontinuity in both the resistance switching processes by DC and pulse voltages. On the other hands, digital resistance switching was dominant in TiN/TaO$_x$/Ta$_2$O$_5$/Pt device. We deduce that the electrodes reactivity with oxygen and the interface resistance play a key role for the analog resistance switching. The analog resistance change speed of 200 ns is much faster than the signal transmission speed between neurons and is thought to increase the number of operations per unit energy consumption. By introducing present RAND, the human-brain inspired information processor is expected to become energetically more efficient.

Index Terms—Nonvolatile memory, Resistive RAM (ReRAM), Analog memory, Neuromorphic

I. INTRODUCTION

Gradually changing phenomena are observed in various situations through nature. For instance, the strength of the synaptic signaling varies continuously depending on the external electrical stimulus [1]. Since energetically efficient information processing realized in our brain is based on the synaptic signaling, an excellent energy-saving information-processing device is expected by mimicking it. The neurons and synapses in our brain play an important role for the electrical signal transmissions which are thought to be considerably related to our recognition, learning, and memory processes. When we focus on one synapse, it receives electrical signals from other plural synapses. The information processing by those synapses have been modeled previously [2, 3] and one synapse can be regarded as the multi-input one-output system called elementary perceptron. The coupling strength between synapses is not constant and it varies on a moment-to-moment-basis depending on the electrical stimulation from other synapses. When we emulate this signal transmission, a certain controllable variable that acts as the coupling strength is required. Here, we focus on the analog resistance change (ARC) induced by the external voltage application. In this case, the resistance value of the device corresponds to the coupling strength. Figure 1(a) and 1(b) compare the elementary perceptron and an example of the simplified device array between the $n$ number of bit lines and one word line. If we apply the voltage of $V_n$ for the $n$-th bit line connecting the device having the conductance of $G_n$, the current value $I$ obtained from the word line in Fig. 1(b) is expressed as $I = \sum_{i=1}^{n} G_n V_n$. This is just the product-sum operation of the inputs in Fig. 1(a). The conductance of $G_n$ in other words, the resistance value of the device acts as the coupling strength. The device layout in Fig. 1(b) is already used for the array structure of ReRAM (resistive random access memory) [4-7] and it can be adapted to the neural network based on the perceptron in Fig. 1(a) [8, 9]. The device structure of ReRAM is quite simple: the oxide thin film sandwiched by the top and bottom electrode (TE and BE) layers. In the case of ReRAM, the digital resistance change (DRC) is observed when the external voltage exceeds a certain threshold voltage value. Therefore, from the view point of the precise and fine control of the resistance values, it is necessary to suppress the rapid resistance change. In this contribution, we demonstrate that ARC can be stabilized.

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II. EXPERIMENTAL

We prepared two types of RAND having different BE material. One BE is TiN and other BE is Pt with Ta as an adhesion layer. Hereafter, we describe RAND with TiN BE and Pt BE as TiN-RAND and Pt-RAND, respectively. For TiN-RAND, TiN BE was prepared by the reactive sputtering process using a metal Ti target. For this reactive sputtering process, the values of the DC power and working pressure are respectively 200 W and 0.065 Pa. The Ar and N gas flow rates are 5 and 1 SCCM, respectively. Under those conditions, the resistivity of the TiN thin film is about 0.15 m Ω cm.

The oxide layer in both devices is composed of Ta2O5 and TaOx. The former was sputter-deposited using a ceramics target and the latter was deposited by the reactive sputtering process. TE for both Pt-RAND and TiN-RAND is TiN. The device size and thickness of BE, Ta2O5, TaOx, and TE are summarized in Table 1. The optical microscopy images and schematic illustrations of the present device structures are shown in Figs. 2(a) and 2(b). In Fig. 2(a), the atomic force microscope (AFM) image near the hole structure is also displayed. In addition, the cross-sectional transmission microscope (TEM) images for TiN-RAND with hole structure with the hole diameter of (c) 1.5 um and (d) 100 nm. In Fig. 2(a), the AFM image of the hole structure with the size of 1.5 um in diameter is also shown. The scale bar in Fig. 2(c) is 500 nm, while that in Fig. 2(d) is 50 nm.

### TABLE 1 Summary of the electrode and oxide materials as well as device structure investigated in this work.

<table>
<thead>
<tr>
<th>Structure</th>
<th>TiN-RAND</th>
<th>Pt-RAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>Hole</td>
<td>Cross-bar</td>
</tr>
<tr>
<td>1.5 um or 100 nm in diameter</td>
<td>50×50-150×150 um²</td>
<td>50×50-150×150 um²</td>
</tr>
<tr>
<td>TE</td>
<td>TiN (60 nm)</td>
<td>TIN (60 nm)</td>
</tr>
<tr>
<td>Oxide</td>
<td>Ta2O5/TaOx (30 nm/4 nm)</td>
<td>Ta2O5/TaOx (30 nm/4 nm)</td>
</tr>
<tr>
<td>BE</td>
<td>TiN (20 nm)</td>
<td>TIN (20 nm)</td>
</tr>
</tbody>
</table>
The resistance change behavior in those devices are unclear in this work, those terms are used for not only the conventional high resistance state (HRS). On the other hands, the set process in DRC. Namely, the reset process is defined as the “reset” and “set” were mainly used for the resistance switching process in DRC. Therefore, the resistance values of those devices do not scale with the device size. This result indicates that the filamentary conduction path is the location of ARC observed in TiN-RAND as is the case in DRC of ReRAM [10-12].

There is a clear difference between the I-V curves of TiN-RAND and that of Pt-RAND. It is a negative differential resistance (NDR) during the reset process. NDS is a negative slope in the I-V curve where the sign of dI/dV becomes negative, which is shown in Fig. 3(a). NDR during the reset process for TiN-RAND is obscure, while that for Pt-RAND is clearer. In the latter case, a large resistance increase occurs even for the slight increase of the external voltage. On the other hands, an unclear NDR in TiN-RAND is thought to be appropriate for ARC. One possible reason for this observed electrode material dependence of RS behavior can be attributed to the work function of the electrode material. Ta₂O₅ is also n-type semiconductor due to oxygen vacancies. The work function (WF) of TiN ( ~ 4.5 eV) is lower than Pt ( ~ 5.6 eV) [13, 14]. Therefore, simply stated, the Schottky barrier height at Ta₂O₅/Pt becomes lower than that at Ta₂O₅/TiN. The voltage drop at the Ta₂O₅/Pt interface becomes larger than that at Ta₂O₅/TiN and it may accelerate the oxidation process at this interface. The polarity of the negative reset voltage corresponds to the forward bias direction for the Schottky barrier at the Ta₂O₅/Pt interface and generally the resistance of this interface for the forward bias direction is smaller than that for the reverse bias direction. However, as observed for some n-type semiconductor oxide materials such as TiO₂ and SrTiO₃, the resistance increase in both the forward and reverse directions is observed with increasing the work function of the electrode materials [15-17].

Another possible reason is the difference in the reactivity with oxygen. TiN is more reactive with oxygen compared to Pt. For the oxide/Pt interface, the oxygen pile up at the interface has been previously proposed [18]. Therefore, the oxygen ions accumulated at the Ta₂O₅/Pt interface can reasonably re-oxidize the Ta₂O₅ layer in LRS during the reset process. On the other hands, the oxidation of TiN electrode is often discussed in ReRAM [19-21]. If there is some leakage of oxygens from Ta₂O₅ to the TiN BE during the reset process, this suppresses the rapid progress of the re-oxidization of Ta₂O₅ and rapid increase of the resistance value.

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FIGURE 3  DC I-V curves for (a) Pt-RAND, (b) TiN-RAND with the cross-bar structure, (c) TiN-RAND with the hole structure with the hole size of 1.5 um, and (d) TiN-RAND with the hole structure with the hole size of 100 nm. NDR in Fig. 3(a) corresponds to the voltage range where the negative differential resistance (NDR) is clearly observed. Red and blue arrows describe the direction of the voltage sweep. Current compliance value for the set process was fixed to be 200 uA.

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of the resistance value of TiN-RAND is clearly observed with increasing the current compliance value. The gradual reset and set processes shown in Figs. 4(a) and 4(b) are also observed in TiN-RAND having the hole structure with the size of 100 nm (Figs. 4(c) and 4(d)). This result implies that the present RAND with ARC can be introduced into the near cutting edge technology node semiconductor process. It should be noted that, except for contact pads of Au/Ti, only TiN, TaOx, and Ta2O5 are used for TiN-RAND and all of the elements consisting those materials are quite familiar with the current semiconductor manufacturing processes.

Figure 5 represents the $V_{\text{reset}}$ dependent set process in TiN-RAND having the hole structure with the size of 100 nm. Different from the $I$-$V$ curve measurements in Figs. 4, the reset and set operations were alternatively conducted with increasing $V_{\text{reset}}$. In addition to the device resistance after the reset process, the subsequent set behavior is also affected by the last reset process. In Fig. 5, the gradual set process is observed for $V_{\text{reset}} = -1.1$ V and -1.3 V (blue dotted and solid curves), while the abrupt resistance decrease similar to DRC is observed for $V_{\text{reset}} = -1.5$ V and -1.7 V (red dotted and solid curves) as indicated by the black arrows. This means that the over reset process should be avoided in order to suppress the abrupt set process.

### B. Resistance change by voltage pulse

In addition to the DC $I$-$V$ curve measurement condition dependence of the RS behavior in TiN-RAND shown in Figs. 4 and 5, we evaluated the resistance change characteristics by applying voltage pulse using TiN-RAND.

Figures 6(a) and 6(b) are the voltage pulse height dependence of the resistance value in TiN-RAND (hole structure, 1.5 um) for the reset and set processes, respectively. Under a certain fixed voltage pulse width condition (from 500 ns to 50 us), the voltage pulse height values were varied from

![FIGURE 4 ARC behaviors in TiN-RAND having the hole structure with the hole size of (a), (b) 1.5 um and (c), (d) 100 nm in diameter. (a) and (c) correspond to the reset process. (b) and (d) correspond to the set process. $V_{\text{reset}}$ in (a) and (c) is the maximum voltage applied during the reset process. Current values of graph legends in (b) and (d) are the current compliance values used during each set processes.](image)

![FIGURE 5 $V_{\text{reset}}$ dependent set process in TiN-RAND having the hole structure with the size of 100 nm. Reset and set operations were alternatively conducted with increasing $V_{\text{reset}}$. Black arrows correspond to the abrupt resistance decrease during the set process observed when $V_{\text{reset}}$ is -1.7 and -1.5 V. Current compliance during the set process is fixed to be 200 uA.](image)

![FIGURE 6 Voltage pulse height dependence of the resistance value in TiN-RAND (hole structure, 1.5 um) for (a) reset and (b) set processes. The schematic explanations on the voltage pulse application step for (a) reset and (b) set processes.](image)
The averaged resistance change per one voltage pulse is about 20 ohm. Compared to the previous report using Pt electrode [22], the fine tuning of the resistance value is realized in the present device. As the control experiment, the RC behavior under the severe reset (-2.0 V/10 us) and set (+1.8 V/500 ns) conditions was also measured (Figs. 7(c) and 7(d)). For such inappropriate conditions, DRC rather than ARC becomes more stable. It is to be noted that the current compliance function of the measurement system is not used for the set processes by the voltage pulse in Figs. 6 and 7, different from the DC I-V measurements in Figs. 4. The external voltage is increased stepwise in the present DC I-V measurements and the duration of each step is longer than 100 ms. It is much longer than the voltage duration that is actually required for the set process. In such DC measurement case, in order to avoid the excessive resistance decrease during the set process, the current compliance function becomes necessary.

One noticeable feature about ARC in TiN-RAND shown in Fig. 7(a) is the speed of RC. The voltage pulse width used here is 200 ns and it is much faster than the information transmission process in the actual neuron. Since the neurons are one of the biological cells, they have a cell membrane which is mainly composed of the lipid bilayer membrane [23]. Since it is somehow insulating, the neurons are considered to be a kind of the capacitor. Therefore, there is a delay in the rate of rise of the neuron action potential. From the previous reports on the time constant \( \tau \) for the neuron cells, the value of \( \tau \) ranges from around 10 to 30 ms [24, 25]. Here, \( \tau \) is generally given as the product of the resistance \( R \) and capacitance \( C \) in the RC circuit as \( \tau = R \cdot C \). In the case of the actual neuron, it is thought that the reduction of \( C \) is difficult because the dimension change of the cell such as the length of the axis cylinder is limited. In contrast, although the basic structure of RAND is also the capacitor in analogy with the neuron cells, the downsizing of RAND is easy to be done by applying the microfabrication process technology as shown in Fig. 2(d). RAND is expected to have not only the similarity in the analog change of the electrical properties with the neuron cell but also the significant advantage in the operating speed of the analog change. This advantage is crucial in order to improve the number of operations per second in the neuron inspired information processor based on RAND.

**IV. CONCLUSIONS**

In conclusion, we successfully demonstrated the very fast analog resistance change (ARC) in the TiN/TaO\(_x\)/Ta\(_2\)O\(_5\)/TiN resistive analog neuromorphic device (RAND). The resistance value of RAND can be finely controlled by the voltage pulse having the pulse width of 200 ns. From the comparison with the TiN/TaO\(_x\)/Ta\(_2\)O\(_5\)/Pt device, the observed ARC in TiN/TaO\(_x\)/Ta\(_2\)O\(_5\)/TiN RAND is considered to be attributed to the lower Schottky barrier height and the consequent smaller interface resistance in Ta\(_2\)O\(_5\)/TiN compared to Ta\(_2\)O\(_5\)/Pt. The observed fast ARC behavior is expected to be the basis for the energetically efficient neuron inspired information processor.
REFERENCES


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