Improved Switching Uniformity of a Carbon-based ReRAM device by Controlling Size of Conducting Filament

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1. Introduction
We investigated the resistive switching properties of a Carbon-based ReRAM device. In order to minimize the fluctuations of switching parameters, we introduced an external load resistor ($R_{\text{load}}$) in series, which indirectly acts as a current limiter. Reduced reset current ($I_{\text{reset}}$) and improved switching uniformity were obtained when the proper external $R_{\text{load}}$ was connected. The voltage drop at the ReRAM device during switching was directly monitored using an oscilloscope.

2. Experimental
As a resistive memory, Cu/carbon/Pt structure resistive memory device was fabricated. The carbon layer was deposited onto a Pt substrate by RF magnetron sputtering at room temperature using a carbon target. Using scanning electron microscopy (SEM) analysis and transmission electron microscopy (TEM) diffraction pattern as shown in Fig. 1(a), we have confirmed a 30 nm-thick amorphous carbon layer as shown in Fig. 1(a). After conventional lithography process, a 100 nm-thick Cu top electrode with an area of 30 x 30 $\mu$m² was formed via sputtering. A schematic diagram of the device structure is shown in inset of Fig. 1(b).

3. Results & Discussion
As shown in Fig. 1 (b), it shows bipolar switching characteristics by the motion of Cu ions. For further understanding about the switching mechanism, the double logarithm plot at set operation region is shown in Fig. 2 (a) which indicates the linear dependence of voltage and current with slope about one [1]. Moreover, we concluded the switching mechanism as the of filamentary theory based on the temperature variable analysis as shown Fig. 2 (b) which consistent with the fact that the resistance of metal is proportional to the temperature [2]. In pulse mode, excess current flowing during the set operation cannot be controlled by the measurement instrument. Because of the nonexistence of $I_{\text{comp}}$ in pulse mode, the excess current forms a thick conductive filament and causes hard failure of the device [3]. To protect the device from excess current flow under pulse switching conditions, an $R_{\text{load}}$ was used to indirectly maintain $I_{\text{comp}}$. The device was connected to $R_{\text{load}}$ (=10 kΩ) only during the set operation. Fig. 3 (a) shows the pulse switching characteristics. We have confirmed stable switching characteristics under pulse switching conditions by adding $R_{\text{load}}$. To clearly understand the effect of $R_{\text{load}}$ on resistive switching, the switching parameters were monitored with varying $R_{\text{load}}$ under DC switching mode. As shown in Fig. 3(b), we found that $I_{\text{reset}}$ is inversely proportional to $R_{\text{CF}}$. High $R_{\text{CF}}$ indicates a smaller-diameter conducting filament (CF), which in turn reduces $I_{\text{reset}}$. To control the size of CF, we intentionally added a series resistor ($R_{\text{load}}$). Fig. 3(c) shows the effect of $R_{\text{load}}$ on $I_{\text{reset}}$. With increasing resistance of $R_{\text{load}}$, $I_{\text{reset}}$ was significantly reduced, indicating a smaller-diameter CF that requires less power to reset. Fig. 4 shows the retention properties at 85 °C as a function of $R_{\text{CF}}$. We found degradation of retention characteristics, which can be explained by the smaller diameter of the CF and migration of copper ions.

4. Summary
For high-density memory applications of ReRAM devices, improved switching uniformity and reduced switching power are required. To solve these problems, we introduced the external series resistor $R_{\text{load}}$. A ReRAM device with $R_{\text{load}}$ shows improved switching characteristics that can be explained by formation of uniform conducting filament. By controlling $R_{\text{load}}$, we can accurately adjust the size and resistance of the conducting filament.

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References
Fig. 1 (a) The plan-view TEM image and the diffraction pattern of carbon layer. (b) I-V hysteresis of Cu/carbon/Pt device. The inset of figure shows the schematic diagram of Cu/Carbon/Pt structure.

Fig. 2 (a) The I-V characteristics in a double-logarithmic plot at the positive bias region. (b) The temperature variable I-V characteristics in range from 150K to 295K.

Fig. 3 (a) Pulse switching properties and the pulse width dependence of the Cu/Carbon/Pt sample using a series resistor. (b) Dependence of reset current on the filament resistance. The data was obtained from fifty DC switching cycles in one spot. (c) The reduced reset current using a series resistor. As the connected resistance increased, the reset current was decreased.

Fig. 4 The retention properties at 85°C for $10^4$ sec. The LRS was programmed using various resistors.

Table 1. The average value of $I_{\text{reset}}$ and standard deviation of $I_{\text{reset}}, V_{\text{set}}$ and $V_{\text{reset}}$

<table>
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<tr>
<th>$R_{\text{Load}}$</th>
<th>AVG of $I_{\text{reset}}$</th>
<th>STD of $I_{\text{reset}}$</th>
<th>STD of $V_{\text{set}}$</th>
<th>STD of $V_{\text{reset}}$</th>
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<td>0.18</td>
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<td>1.3E-4</td>
<td>0.16</td>
<td>0.047</td>
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<td>0.046</td>
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<td>1.4E-5</td>
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