Highly uniform low-power resistive memory using nitrogen-doped tantalum pentoxide


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Highly uniform current distributions of high resistance state (HRS) and low resistance state (LRS), low 0.6 pJ switching energy, fast 30 ns switching speed, and good 10⁶ cycling endurance are achieved in Ni/GeO/Ta₂O₅₋ₓNₓ/TaN resistive random access memory (RRAM) devices. Such good performance is attributed to nitrogen-related acceptor level in Ta₂O₅₋ₓNₓ for better hopping conduction, which leads to forming-free resistive switching and low self-compliance switching currents.

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In this paper, we report an ultra-low 0.6 pJ switching energy GeO/TaON RRAM with much tighter distribution and more stable endurance to 10⁶ cycles. Such excellent performance is attributed to low self-compliance set/reset currents with the hopping conduction via nitrogen defects which is different to reported Pt/TaOₓ/Pt RRAM [11] with a large-size transistor to drive high current compliance.

The RRAM devices were integrated into VLSI backend with a 200-nm SiO₂ on a Si substrate. Then 100 nm TaN was deposited by physical vapor deposition (PVD). After patterning the TaN electrode, the 36-nm-thick Ta₂O₅₋ₓNₓ film remained amorphous phase after annealing which has been examined by X-ray diffraction (XRD). The control Ta₂O₅ layer was also deposited for performance comparison. After that, a 50-nm-thick Ni was deposited and patterned as top electrode by a metal mask with an area of 11,300 μm².

Fig. 1a shows the swept I–V curves of the Ni/GeOₓ/Ta₂O₅₋ₓNₓ/TaN and control Ni/GeOₓ/Ta₂O₅/TaN RRAM devices, and the swept...
directions were indicated by the arrows. The resistance changes from high resistance state (HRS) to low-resistance state (LRS) during set process, and changes from LRS to HRS during reset. The needed forming-free and self-compliance resistive switching characteristics are obtained in Ni/GeO$_x$/Ta$_2$O$_5$-yNy/TaN RRAM device; however, the control Ni/GeO$_x$/Ta$_2$O$_5$/TaN device requires additional current-compliance to avoid breakdown during set/reset operations. The current-compliance will require a transistor to deliver and limit the set current, but the extra transistor consumes a larger area. The nitrogen-incorporated Ni/GeO$_x$/Ta$_2$O$_5$-yNy/TaN RRAM device shows a resistance ratio $>100$ at 0.2 V read, a low set power of 19 $\mu$W (3.8 $\mu$A at 5 V) and reset power of 12 $\mu$W (−2 $\mu$A at −6 V). The low self-compliance currents during set/reset operation are related to the large internal resistance in nitrogen-doped RRAM device by hopping conduction [13].

To further investigate the nitrogen-doping effect, we have plotted the HRS/LRS current distributions in Fig. 1b. The control RRAM device, even with additional current-compliance, still exhibits wide LRS and HRS current distributions, which may be ascribed to random distribution of oxygen vacancies in Ta$_2$O$_5$ dielectric. In sharp contrast, highly uniform LRS and HRS currents and $>100$ resistance ratio are found in the nitrogen-doped RRAM device that is even better than published GeO$_x$/HfON RRAM [13]. The excellent switching uniformity is linked to the low power operation of forming-free resistive switching and low self-compliance set/reset currents, which have less stress to the dielectric of metal–insulator–metal (MIM) RRAM devices. This is significantly better than conventional RRAM using metallic filament conduction.

To explore such uniform switching currents, the current conduction mechanism was analyzed. Fig. 2a shows the measured and simulated $I$–$V$ characteristics at HRS and LRS, respectively.

![Figure 1](image1.png)  
**Fig. 1.** (a) Swept $I$–$V$ curves and (b) set/reset current distributions of Ni/GeO$_x$/Ta$_2$O$_5$-yNy/TaN and control Ni/GeO$_x$/Ta$_2$O$_5$/TaN RRAM devices. The arrows indicate the bias sweeping directions.

![Figure 2](image2.png)  
**Fig. 2.** (a) Measured and simulated HRS and LRS currents, (b) $C$–$V$ curves at HRS and LRS and (c) the schematic energy band diagrams under set and reset conditions of Ni/GeO$_x$/Ta$_2$O$_5$-yNy/TaN RRAM devices.

![Figure 3](image3.png)  
**Fig. 3.** The XPS spectra of Ta 4f and N 1s core level in Ta$_2$O$_5$-yNy.
The small HRS current is due to the Frenkel–Poole conduction [17] via the top Ni electrode. The current at LRS is governed by the space-charge-limited current (SCLC) via dielectric defects, for electrons injected from the bottom TaN electrode. This will create more dielectric charges \( \Delta Q_d \) in the MIM RRAM capacitor. During the reset, the electrons were injected from the top high work-function Ni electrode to neutralize charged vacancies and thereby break the hopping conduction pass [13]:

\[
V^{n+} + ne^- \rightarrow V^o.
\] (1)

Here the \( V^o \) is the neutralized vacancy state in the dielectric. Since the voltage differences for process 4 and 1, or 2 and 3 are the same, the extra larger \( \Delta Q_d \) is measurable by the higher capacitance. The above explanation and related mechanism are shown schematically in Fig. 2c. The hopping conduction also provides a large increase of the leakage current, fast 30 ns switching time and excellent 10^6 cycling endurance in addition to a tight current distribution.

In summary, the nitrogen-doped Ni/GeO\textsubscript{x}/Ta\textsubscript{2}O\textsubscript{5}/N\textsubscript{2}/TaN RRAM shows low 0.6 pJ switching energy, fast 30 ns switching speed, and good 10^6 cycling endurance, which is ascribed to nitrogen-related acceptor level in Ta\textsubscript{2}O\textsubscript{5}/N\textsubscript{2} for better hopping conduction, forming-free resistive switching, and low self-compliance currents.

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**References**


**Table 1**

Comparison of device integrity data for various RRAM devices.

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<tbody>
<tr>
<td>( I_{SET} )</td>
<td>0.6 mA, 3.9 V</td>
<td>–1 mA, –1 V</td>
<td>10 mA, 0.8 V</td>
<td>–170 ( \mu )A, –0.9 V</td>
<td>0.1 ( \mu )A, 3 V</td>
<td>3.8 ( \mu )A, 5 V</td>
</tr>
<tr>
<td>( I_{RESET} )</td>
<td>5 mA, 1.4 V</td>
<td>1 mA, 1.1 V</td>
<td>–5 mA, –1.5 V</td>
<td>170 ( \mu )A, 2 V</td>
<td>–0.3 ( \mu )A, –1.8 V</td>
<td>–2 ( \mu )A, –6 V</td>
</tr>
<tr>
<td>Self-compliance</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>HRS/LRS</td>
<td>(~2 \times 10^2)</td>
<td>(~10^7)</td>
<td>(~10^1)</td>
<td>(~10)</td>
<td>9 ( \times 10^2)</td>
<td>10^2</td>
</tr>
<tr>
<td>Cycles, pulse</td>
<td>10^6, 5 ns</td>
<td>200 dc cycles</td>
<td></td>
<td></td>
<td>10^4, 100 ns</td>
<td>10^5, 20 ns</td>
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**Fig. 4.** (a) Endurance and (b) 85 °C retention characteristics of Ni/GeO\textsubscript{x}/Ta\textsubscript{2}O\textsubscript{5}/N\textsubscript{2}/TaN RRAM devices.

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