Extreme environment devices, AI hardware

# Development of memristor devices operable under harsh environments

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Researchmap https://researchmap.jp/read0192520?lang=en

## Abstract

In sectors such as automotive, aerospace, and IoT, next-generation memory devices that can maintain stable operation under harsh conditions are crucial. Memristors, a type of Resistive Random Access Memory device utilizing metal oxides, have garnered substantial research interest due to their capability to exhibit non-volatile resistance changes by redistributing internal oxygen vacancy ions. Their simplicity in structure and low power consumption further boost their appeal. We successfully fabricated memristors using reduced amorphous gallium oxide (a-GaOx), a wide-bandgap semiconductor, as thin films through pulsed laser deposition, demonstrating stable operation at high temperatures. Unlike conventional silicon-based memory devices, which experience reliability issues at temperatures above 125 ℃, a-GaOx memristors retained stable memory characteristics even beyond 300 ℃. To facilitate advancements in high-density 3D-integrated circuits, we successfully fabricated a-GaOx crossbar array memristors comprising fine upper and lower electrode bars.

## Background & Results

Emerging fields such as space exploration, geothermal energy, nuclear power, and aerospace systems require control devices capable of high-temperature operation. Developing memristors that function reliably in harsh conditions is essential for these technologies. Conventional “filament-type” memristors, which achieve high resistance ratios through the formation of conductive filaments, present challenges due to difficulties in controlling the formation position and size of the filaments, causing performance inconsistency and reliability concerns. Our research, in contrast, focuses on “non-filamentary” memristors, achieving resistive switching by precisely controlling the distribution of oxygen vacancy ions within metal oxides. We developed a capacitor-type memristor with gallium oxide by creating a thin, reduced amorphous film, just tens of nanometers thick, using pulsed laser deposition. The a-GaOx memristor displayed a “counter figure-8 hysteresis” in its current-voltage characteristics, reflecting its non-filamentary memory behavior. Specifically, this effect arises when positively charged oxygen vacancies move toward the upper electrode under negative voltage, creating a low-resistance state, and are repelled under positive voltage, producing a high-resistance state (see Figure 1). This hysteresis was observed even at temperatures up to 600 K (327 ℃), with memory functionality maintained over extended durations, demonstrating the exceptional high-temperature endurance of a-GaOx memristors. Additionally, by employing microfabrication techniques like electron beam lithography, we successfully built a-GaOx crossbar array memristors with potential for high-density 3D integration (see Figure 2). Essential characteristics for neuromorphic computing applications, such as non-volatile retention exceeding 10,000 seconds, multi-level conductance modulation, and spike-timing-dependent plasticity, were confirmed. These results demonstrate that a-GaOx crossbar array memristors are a promising hardware platform for AI edge devices.

## Significance of the research and Future perspective

The a-GaOx memristor, beyond its typical use as a storage device, can function as an artificial synaptic device in artificial neural networks through its crossbar array structure. The newly developed high-temperature-resistant a-GaOx memristor exhibits high potential for application in AI edge devices capable of stable operation even under harsh environmental conditions.

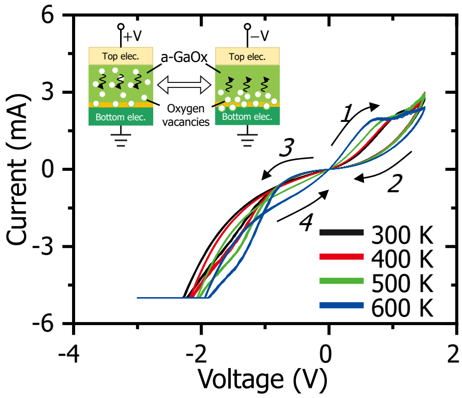


Figure 1: Current-voltage characteristics of a reduced amorphous gallium oxide memristor. Non-filamentary resistive switching occurs with an counter ‘figure-eight’ hysteresis loop following the sequence 1 → 2 → 3 → 4, even at a high temperature of 600 K (327 °C).

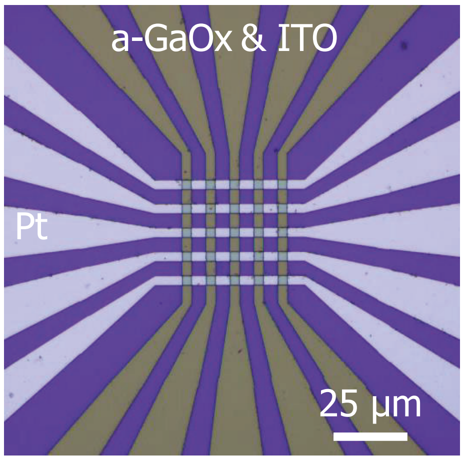


Figure 2: Optical microscope image of a crossbar array memristor using reduced amorphous gallium oxide. The size of the cross-points sandwiched between the Pt and ITO electrode bars is 3 μm × 3 μm.

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| Patent | Japanese Patent No.7591784 |
| Treatise | Sato, Kento; Hayashi, Yusuke; Sakai, Akira et al. High-temperature operation of gallium oxide memristors up to 600 K. Scientific Reports. 2023, 13, 1261. doi: 10.1038/s41598-023-28075-4<br>Masaoka, Naoki; Hayashi, Yusuke; Sakai, Akira et al. Interface engineering of amorphous gallium oxide crossbar array memristors for neuromorphic computing. Japanese Journal of Applied Physics. 2023, 62, SC1035. doi: 10.35848/1347-4065/acb060 |
| URL | |
| Keyword | memristor, Resistive Random Access Memory, high-temperature operation, gallium oxide, AI |