Journal of Neuromorphic Intelligence

PERSPECTIVE

VOLUME 03 | APRIL 2026

Neuromorphic Electronics Beyond Earth: Opportunities in Microgravity Manufacturing

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ABSTRACT

Microgravity manufacturing provides a new pathway for producing neuromorphic electronic devices in space, offering both logistical advantages for long-duration missions and unique opportunities to tailor device performance through unique process physics. Recent studies demonstrate that microgravity can modify device manufacturing dynamics, defect structures, and switching behavior, leading to reduced operating voltage, improved stability, and enhanced neuromorphic functionality compared to ground-fabricated counterparts.

Keywords: ***neuromorphic electronics, in-space manufacturing, microgravity, resistive switching devices***

MAIN TEXT

For long-duration and deep-space missions, the growing distance from Earth and the increasing duration of operation are driving demand for more flexible and responsive supply capabilities. Among spacecraft subsystems, electronics are especially important because they support core mission functions, including communication, navigation, power regulation, data acquisition, and scientific instrumentation, making in-space manufacturing and repairing of electronic components critical. Neuromorphic devices are particularly appealing because they offer a route to compact, low-power, and functionally adaptive electronic hardware for future space systems[1], where onboard autonomy and efficient information processing are increasingly critical[2].

In this context, in-space manufacturing offers a valuable route for the on-demand production of mission-critical components and functional devices. At the system level, such capabilities could also help address the broader spare-parts burden of long-duration missions as analyses indicate that over 95% of spares allocated for random ISS failures may remain unused[3]. Beyond logistics, microgravity alters processing physics of electronics fabrication by suppressing buoyancy-driven convection and changing flow, wetting, and solidification behavior. A meta-analysis of 160 semiconductor crystal-growth experiments found that 86% of comparable materials improved at least one metric under microgravity[4]. Into the device level, Jiang et al.[5] demonstrated microgravity-compatible manufacturing of a fully printed flexible humidity sensor by electrohydrodynamic (EHD) inkjet printing, with parabolic-flight tests showing printed patterns of comparable quality to ground samples.

Recent advances in microgravity manufacturing suggest that the space

Received: 22 March 2026

Accepted: 1 April 2026

Published: 6 April 2026

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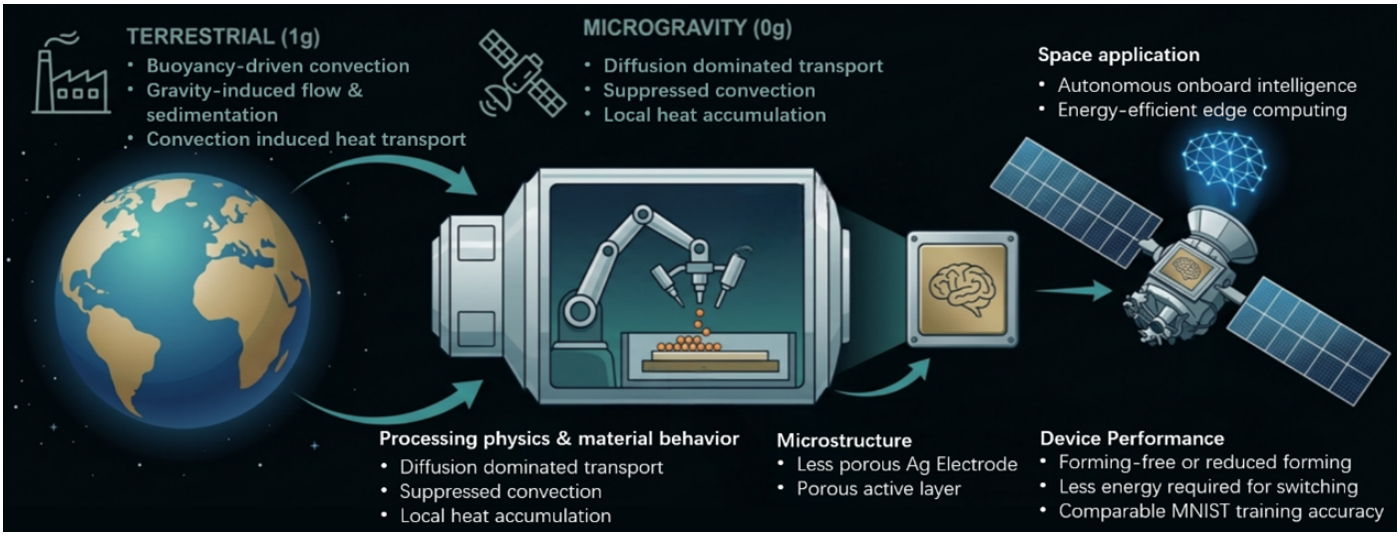


Figure 1: An illustrative summary of microgravity manufactured neuromorphic device features

environment may serve not only as a fabrication setting, but also as a platform for producing neuromorphic devices with behaviors and performance distinct from their ground-manufactured counterparts. As shown in Figure 1, Such devices could support low-power, autonomous onboard processing for future space missions, including sensing, data reduction, and fault monitoring under energy-constrained and communication-limited conditions[6]. Huang et al.,[7] reported microgravity environment fabricated ZnO-based resistive memory devices exhibited distinct devices behavior compared to ground fabricated ones. A summarize of performances comparing microgravity- and ground-fabricated devices are shown in Table 1. Specifically, devices fabricated under microgravity exhibit an 89.3% reduction in electroforming and switching voltage (from 16.0 V to 1.7 V) relative to ground-fabricated counterparts, corresponding to a substantial decrease in operating energy and enabling low-power synaptic operation. This improvement was attributed to the porous oxide layer with abundant oxygen vacancies, which facilitates conductive filament formation with reduced energy input. Beyond the pronounced reduction in operating power, microgravity-fabricated devices show narrower high- and low-resistance-state (HRS/LRS) distributions and enhanced cycle-to-cycle consistency, supporting more predictable and reproducible synaptic weight updates. Under reduced programming voltages (≈1–1.2 V), microgravity-fabricated devices further demonstrate more linear and symmetric long-term potentiation and depression (LTP/LTD) characteristics, which are favorable for training accuracy, convergence behavior, and energy-efficient learning in neuromorphic systems.

Table 1 : Performance comparison of ZnO-based RRAM fabricated on terrestrial and microgravity conditions [7]

Metric	Ground-fabricated	Microgravity-fabricated
Fabrication environment	1 g (Earth)	≈0 g (parabolic flight)
Electroforming voltage	≈16 V	≈1.7 V (89.3% reduction)
Minimum forming power	2.12 mW	76.2 μW
Memory window (on/off ratio)	≈5	≈257
HRS/LRS current distribution	Broad distributions	Narrower distributions
Switching voltage stability	Stable, higher voltage	Lower and more stable RESET voltage
Retention	HRS stable; LRS unstable beyond ≈2500 s	Stable HRS and LRS up to 10^4 s
LTP/LTD linearity (R^2)	LTP ≈ 74.4%; LTD ≈ 32.2%	LTP ≈ 54.3%; LTD ≈ 79.2%
MNIST accuracy	≈90%	≈90%

In addition, Jiang et al[8]., reported the parabolic-flight demonstration of electrohydrodynamic (EHD) printing of ZnO-based resistive switching neuromorphic device, which established the first fully printed functional memory device fabricated under microgravity. EHD process produced narrower lines under microgravity (~56 μm at 2200 V versus ~81 μm at 1800 V on Earth) as compared to the same ground-based printing regime. At the same time, microgravity yielded denser, less porous, and lower-resistance printed Ag electrodes, with the finest line width reaching 23 μm. The microgravity-printed device showed switching behavior comparable to its ground-fabricated counterpart. But a clear advantage is that it switched directly without electroforming, with SET and RESET voltages of 0.7 and –1.78 V, respectively. By contrast, the ground-printed device began in a high-resistance pristine state and required forming up to 20 V, along with a higher compliance current, before stable switching could be achieved.

Overall, these studies indicate that microgravity is not merely an operating environment for neuromorphic hardware, but also a manufacturing condition capable of altering process physics, microstructure evolution, and device functionality. It is interesting to point out that in-space manufacturing may support not only on-demand electronics production for long-duration missions, but also the realization of neuromorphic devices with performance characteristics difficult to achieve under terrestrial conditions. Although current demonstrations are largely limited to parabolic-flight conditions, the broader space environment including vacuum, radiation, and thermal cycling. These factors remain to be assessed. Even so, the field shows clear promise. Moving forward, systematic study of the relationships among space manufacturing conditions, defect evolution, and device performances will be essential, along with validation of long-term reliability, scalability, and suitability for autonomous space systems.

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COMPETING INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ACKNOWLEDGMENTS

The authors are grateful for the funding support from Beihang University