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$LiNbO_3$-based memristors for neuromorphic computing applications: a review

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Neuromorphic computing is a promising paradigm for developing energy-efficient and high-performance artificial intelligence systems. The unique properties of lithium niobate-based ($LiNbO_3$)-based memristors, such as low power consumption, non-volatility, and high-speed switching, make them ideal candidates for synaptic emulation in neuromorphic systems. This study investigates the potential of $LiNbO_3$-based memristors to revolutionize neuromorphic computing by exploring their synaptic behavior and optimizing device parameters, as well as harnessing the potential of $LiNbO_3$-based memristors to create efficient and high-performance neuromorphic computing systems. By realizing efficient and high-speed neural networks, this literature review aims to pave the way for innovative artificial intelligence systems capable of addressing complex real-world challenges. The results obtained from this investigation will be crucial for future researchers and engineers working on designing and implementing $LiNbO_3$-based neuromorphic computing architectures.

KEYWORDS

neuromorphic computing, LiNbO3-based memristors, synaptic behavior, nonlinear optical properties, artificial intelligence, advanced fabrication techniques, synaptic plasticity

Introduction

The quest for energy-efficient and high-performance computing systems has led to exploring novel materials for applications in emerging paradigms, such as neuromorphic computing. Neuromorphic computing (Marković et al., 2020), inspired by the remarkable efficiency of the human brain, has emerged as a promising alternative to traditional computing paradigms for building energy-efficient and high-performance artificial intelligence systems. This field focuses on developing brain-inspired architectures that mimic neural networks' parallel and distributed processing capabilities. A crucial component of neuromorphic systems is the memristor (Volos et al., 2015), the fundamental building block that emulates synaptic behavior and enables efficient learning and adaptation in neural networks.

Among various materials investigated for memristor technology, $LiNbO_3$-based memristors (Chua, 1971) have garnered significant attention due to their unique combination of properties. The ferroelectric nature, electro-optic properties, non-volatility, low power consumption, high-speed switching, and the capability for multi-level resistance states collectively position $LiNbO_3$ as a multifaceted material for developing efficient and brain-inspired computing architectures. Accordingly, the exploration of $LiNbO_3$ in neuromorphic computing stems from its potential to mimic synaptic

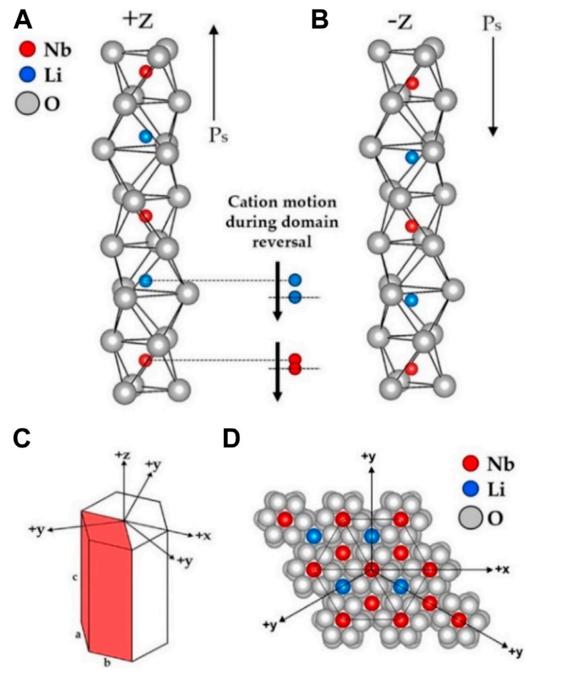

FIGURE 1
The crystal structure of ferroelectric $LiNbO_3$ shows two potential cation displacement scenarios relative to each equidistant oxygen octahedron. In **(A)**, the orientation shows Z+ cation displacement, while in **(B)**, it illustrates Z-cation displacement. **(C)** exhibits the conventional choice of axes for the "ortho-hexagonal" setting (*XYZ*) about the hexagonal setting (*a, c*). Note that all axes possess equal lengths in the hexagonal setting, whereas in the Cartesian setting, they differ. **(D)** presents a projection of the atomic arrangement along the c-axis (Sánchez-Dena et al., 2020).

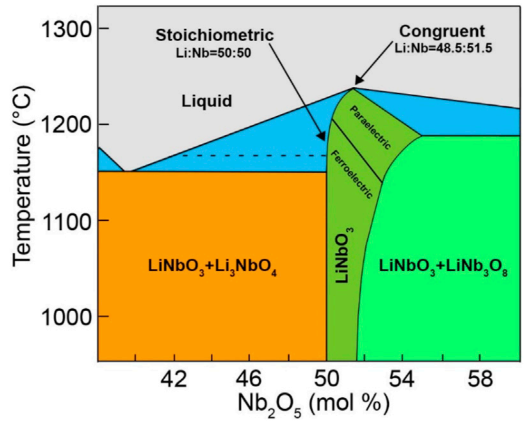

FIGURE 2
Schematic phase diagram of the $Li_2O—Nb_2O_5$ pseudo-binary system near the congruent and stoichiometric composition of $LiNbO_3$ (Narayanareddy, 2008; Sánchez-Dena et al., 2020; Chen et al., 2021b).

behavior and facilitate energy-efficient computing processes (Saleh and Koldehofe, 2022; Xu et al., 2023).

The ferroelectric nature of $LiNbO_3$

$LiNbO_3$ is a ferroelectric material with multiple invaluable technological applications. Ferroelectricity in lithium niobate crystals can be attributed to face-sharing octahedra aligned along the crystal's *c*-axis (Xue and Kitamura, 2003). In neuromorphic computing, a material's ferroelectric nature becomes particularly intriguing due to its potential to mimic synaptic behavior—a key aspect of artificial neural networks inspired by the human brain (Suna et al., 2022; Wang et al., 2022; Xu et al., 2023). The study of $LiNbO_3$ in neuromorphic computing is relevant in pursuing efficient and brain-like computing architectures. $LiNbO_3$'s ferroelectricity property is crucial for emulating synaptic plasticity, allowing for the adjustment of synaptic weights in response to external stimuli (Wang et al., 2022; X; Pan et al., 2019; Wang et al., 2023a; Dongale et al., 2017). The reversible polarization of $LiNbO_3$ aligns with the dynamic nature of synapses, providing a foundation for the material's application in neuromorphic systems. The inherent ferroelectric nature of $LiNbO_3$, characterized by spontaneous polarization (Birnie, 1990; Yoo et al., 2018), domain structures (McConville et al., 2020), and piezoelectricity (Vakulov et al., 2020; Chen et al., 2021a; Kislyuk et al., 2022), justifies its multifaceted utility. These articles serve as key references in comprehending the fundamental aspects of $LiNbO_3$'s ferroelectric nature.

The spontaneous electric polarization that $LiNbO_3$ exhibits can be reversed by applying an external electric field (Roshchupkin et al., 2009; Stone et al., 2011; Tayi et al., 2012). Besides, $LiNbO_3$ crystallizes in the trigonal structure belonging to the R3c space group (Inbar and Cohen, 1997; Sánchez-Dena et al., 2020; Chen et al., 2021b; Palatnikov et al., 2023). The crystal structure comprises corner-sharing NbO_6 octahedra and Li ions occupying interstitial sites (Nico et al., 2016). The non-centrosymmetric structure also contributes to the material's ferroelectric properties (Sánchez-Dena et al., 2020). Additionally, $LiNbO_3$ undergoes a ferroelectric phase transition at a high Curie temperature (T_C) of between 1,141 and 1,210°C (McConville et al., 2020), where ferroelectric properties, including the spontaneous polarization, disappears (Voskresenskii et al., 2017; Lin et al., 2018; Chen et al., 2021a). Figure 1 illustrates the crystalline structure of $LiNbO_3$ exhibiting ferroelectric properties with a stoichiometric composition that remains stable for temperatures below the curie temperature. The Curie temperature shifts depending on the chemical composition. The basic net consists of six evenly spaced layers of oxygen per unit length, arranged along the polar axis *c*.

$LiNbO_3$ has advantageous ferroelectric properties over other perovskite materials, making it a prominent candidate for various neuromorphic applications. Its high Tc ensures stability over a wider range of operating conditions than its counterparts, including lead zirconate titanate (PZT) (Hwang et al., 1998; Wolf and Trolier-McKinstry, 2004), barium strontium titanate (BST) (Ioachim et al., 2007; Gatea and Naji, 2020), strontium titanate (SrTiO3) (Li et al., 2004; Dec et al., 2005; Gatea and Naji, 2020), barium titanate (BaTiO3) (Sakayori et al., 1995; Chlup et al., 2023), and lead magnesium niobate-lead titanate (PMN-PT) (Ivan et al., 2012), which have much lower Curie temperatures. Below T_C, $LiNbO_3$ exhibits ferroelectric properties, and above it, the material becomes paraelectric. Multiple studies have also shown $LiNO_3$'s sensitivity to the chemical composition (CC) on the whole range of the $LiNbO_3$'s single phase, as shown in Figure 2.

The binary phase diagram in Figure 2 shows the wide solid solution range exhibited by $LiNbO_3$. This solution can be stable on lithium composition between 46.5 and 50 mol%. The diffuse peak at around 48.5% Li_2O is evident in the liquid–solid curve, beyond which the formation of secondary phases such as $LiNb_3O_8$ and Li_3NbO_4 can occur (Chen et al., 2021a).

The ferroelectric property makes lithium niobate have significant applications in various fields, including optics, acoustics, and information processing (Edon et al., 2009; Wu et al., 2020; Chen et al., 2021b; Lin et al., 2022). For instance, $LiNbO_3$ is applied in polarization management due to high fidelity polarization generation with an extinction ratio that can exceed 41.9 dB and a high polarization scrambling rate of over 64 Mrad s^{-1} (Lin et al., 2022; Hou et al., 2023).

Piezoelectric phenomena in $LiNbO_3$

While investigating the piezoelectric nature of $LiNbO_3$, studies have offered a detailed exploration of the material's response to mechanical stress (Du et al., 2007; Zhang et al., 2019). $LiNbO_3$'s non-centrosymmetric crystal structure imparts unique electrical properties upon applying mechanical stress. Research has elucidated the crystal's anisotropic nature, emphasizing its sensitivity to different stress directions (Weis and Gaylord, 1985; Rivera et al., 2011; Gruber et al., 2018). Accordingly, studies underscore the intricate relationship between ferroelectricity and piezoelectricity in $LiNbO_3$, showcasing its potential for applications in sensors, actuators, and other electromechanical devices (Chen et al., 2021a) $LiNbO_3$ also exhibits strong electro-optic effects (Meng et al., 2007) Accordingly, it is extensively used in the field of telecommunications for the development of modulators since the electro-optic effect in LiNbO3 enables the modulation of light signals, which is crucial in devices like electro-optic modulators used in fiber-optic communication systems. Besides, $LiNbO_3$ offers superior piezoelectric coefficients and mechanical stability compared to other perovskite materials, such as PZT, BST, $SrTiO_3$, $BaTiO_3$, and PMN-PT (Sumets, 2018). These properties make $LiNbO_3$ ideal for use in ultrasonic transducers, acoustic wave devices, and actuators, where high sensitivity and durability are paramount. As a material with a rich tapestry of properties, $LiNbO_3$ continues to captivate researchers, laying the groundwork for innovations across diverse scientific disciplines, including neuromorphic computing.

Non-volatility and low power consumption

Although lithium niobate is not typically associated with memory retention in the same way as traditional electronic materials used in computer memory, such as silicon-based technologies, it has been explored for multiple applications, including non-volatile memory and optical memory devices. The non-volatile characteristics of $LiNbO_3$ play a pivotal role in reducing the power requirements for maintaining synaptic weights. One of the defining features that positions $LiNbO_3$ as a frontrunner in neuromorphic computing is its non-volatile nature, which allows for the retention of synaptic weights even when power is removed. Xu et al. (2023) and Wang et al. (2015) discuss how this characteristic allows for the retention of synaptic weights even in the absence of power, mimicking the persistent connectivity of biological synapses. Besides, Wang et al. (2017) show that the ferroelectric property of $LiNbO_3$ enables the retention of synaptic weights even when power is removed. This persistence aligns with the essence of non-volatile memory, mirroring the sustained connectivity observed in biological synapses. The non-volatile aspect is fundamental for the stability and integrity of neural networks.

In Figure 3A left, a $LiNbO_3$ device retention test was conducted as the device was set to R_{MIN} and was measured at regular intervals within 24 h. Data reveals negligible variation in the programed device state when measured at room temperature over that period. Figure 3A right shows the results of a retention test on a $LiNbO_3$ device at different temperatures, considering a programmed intermediate state at approximately 1 mA. The tests were also performed on the $LiNbO_3$ device at temperatures between 20 and 100°C (Wang et al., 2017). Results showed negligible current change as device temperatures are increased. Likewise, Figure 3E illustrates how $LiNbO_3$ device demonstrates outstanding data retention performance over 27.7 h at room temperature. Additionally, Figure 3F shows conductance undergoes only a 0.74% decay process after approximately 16.7 h from programming the device to a high conductance state, as it remains stable without degradation. As a result, Wang et al. (2023c) speculates that the device retention lifetime at room temperature can be up to 10 years.

$LiNbO_3$-based memristors also exhibit low power consumption, addressing the demand for energy-efficient computing systems, as revealed by Zaman et al. (2017), Xu et al. (2023), Wang et al. (2015), and Nakajima et al. (2022). Examining the energy efficiency of $LiNbO_3$, Zaman (2020) discusses how the material's non-volatility contributes to low power consumption during synaptic emulation. Besides, research emphasizes that the inherent properties of $LiNbO_3$ allow for efficient information storage and retrieval, facilitating energy-conscious neuromorphic operations (Chaudhary et al., 2020). This breakthrough aligns with the broader goal of creating sustainable and environmentally friendly computing architectures. Through advanced fabrication techniques, studies demonstrate that $LiNbO_3$ memristors can achieve efficient and stable operation with minimal power requirements (Zaman et al., 2019; Huang et al., 2021; Liang et al., 2021). For instance, lithium niobate's non-volatility, coupled with its minimal power requirements during read and write operations and low operating voltages as shown to be ~1.20 V at room temperature and ~0.95 V at 95°C for a bilayer $LiNbO_3$-based memristor device, makes LiNbO3-based memristors competitive against alternatives such as $SrTiO_3$ and $BaTiO_3$ (Zaman et al., 2020). Such experimental validations reinforce the theoretical understanding of $LiNbO_3$ as a material capable of supporting low-power neuromorphic computations.

In the pursuit of prolonged neural network operations (Wang et al., 2023b), shed light on $LiNbO_3$'s role in enabling persistent synaptic connections. The non-volatile property of $LiNbO_3$ ensures that the information encoded in synaptic weights remains intact over extended periods. This feature is particularly crucial for applications requiring continuous learning and adaptation, positioning $LiNbO_3$ as a material with profound implications for

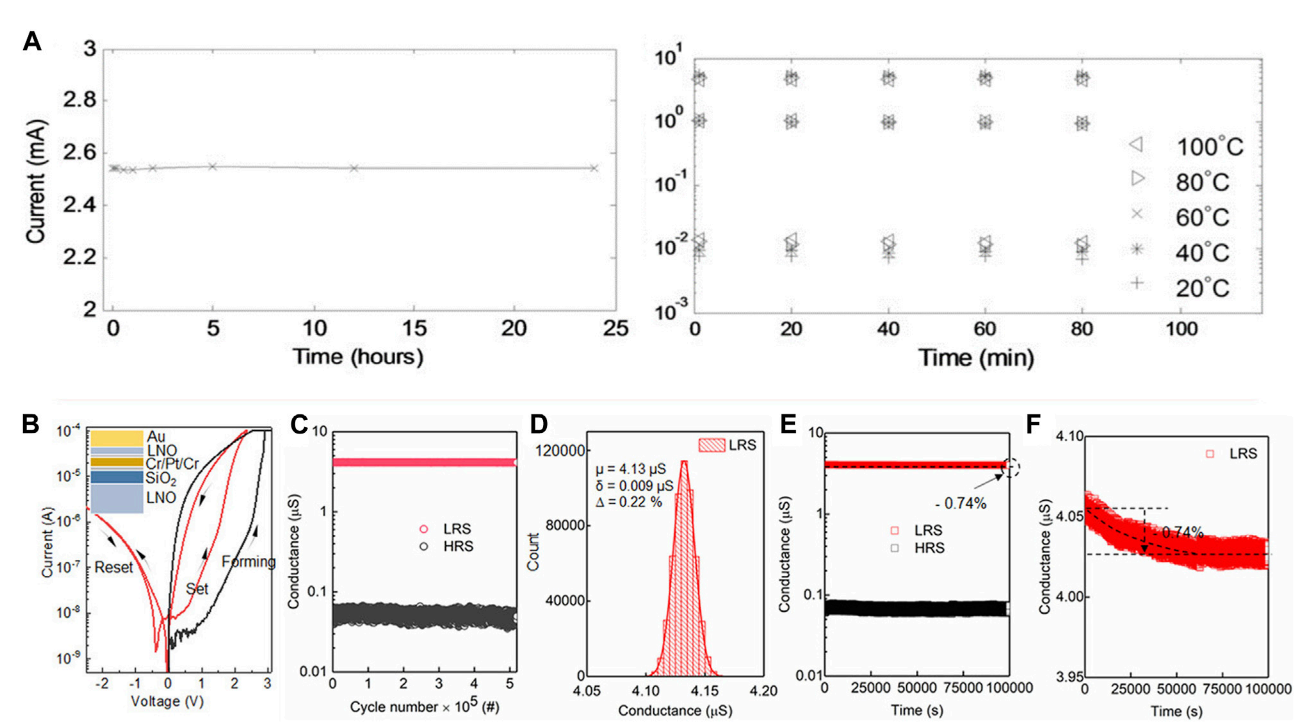

FIGURE 3
(A) Shows a retention test to prove the non-volatility characteristics of $LiNbO_3$ memristor (Wang et al., 2017). **(B)** Shows the electroforming process and resulting I–V curve are typical, with a cross-sectional diagram of the memristor showing its structure as Au/LNO/Cr/Pt/Cr. In **(C)**, device endurance is demonstrated over 5×10^5 cycles with a switching window of 80, indicating robust performance. **(D)** Reveals detailed statistical analysis that the device effectively switches with minimal fluctuations, as evidenced by the Normal distribution function fitting of the low-resistance state (LRS). Just as in **(A)**, **(E)** reveals that retention testing over a prolonged period of 10^5 s shows stable behavior. **(F)** Detailed analysis of LRS retention over the same period indicates minimal conductance decay, with stability maintained for approximately 16.7 h after programming the device to a high-conductance state (LRS) (Wang et al., 2023b).

the longevity of neuromorphic systems. As this field advances, integrating $LiNbO_3$ into neuromorphic architectures holds promise for creating sustainable, high-performance artificial intelligence systems. Likewise, non-volatile memory is crucial for retaining information even when power is disconnected, offering energy efficiency and data persistence advantages. Sun et al. (2023) explore the implications of $LiNbO_3$'s ferroelectricity in non-volatile memory applications. The study investigates ferroelectric field-effect transistors based on $LiNbO_3$, highlighting its potential for high-density memory storage. This work underlines the relevance of $LiNbO_3$'s ferroelectric nature in advancing data storage technologies. Indeed, $LiNbO_3$-based memristors exhibit low power consumption and efficient memory retention, crucial for extending the operational life of neural network systems, especially in scenarios where energy conservation is imperative.

High-speed switching and synaptic plasticity

High-speed switching and synaptic plasticity support neuromorphic computing systems' dynamic learning and adaptation processes. Multiple studies collectively reveal the important role of $LiNbO_3$ in enabling high-speed switching and synaptic plasticity within neuromorphic computing. $LiNbO_3$'s high-speed switching capability is critical for emulating synaptic plasticity in neuromorphic systems. For instance, Figure 3B illustrates the typical electroforming process and successive I–V sweeps for the LNO-based devices. Following electroforming, the device exhibits analog switching behavior. According to J. Wang et al. (2023c), Ar^+ beam irradiation allows the device to acquire switching characteristics and significantly reduces the operating voltage. Figure 3C shows the endurance property of the $LiNbO_3$ memristor, demonstrating reliable endurance characteristics. More detailed cyclic switching analyses are depicted in Figure 3D in which the cyclic conductance states show that the device effectively switches in every cycle without becoming stuck at any state. Indeed, memristors based on $LiNbO_3$ have demonstrated rapid switching speeds, enabling efficient adaptation to changing neural network conditions (Yakopcic et al., 2017; Eid et al., 2020; Wang et al., 2023a). Emulating synaptic plasticity is crucial for learning and memory functions in artificial neural networks. Yakopcic et al. (2017) elaborate on the significance of rapid switching in neuromorphic computing, highlighting how it facilitates the swift adaptation of synaptic weights—a fundamental requirement for learning and memory functions in artificial neural networks.

Research has also focused on realizing synaptic plasticity in $LiNbO_3$-based memristors. For instance, Wang et al. (2022) and Liang et al. (2021) demonstrate the material's efficacy in emulating the plastic nature of biological synapses, demonstrating the potential for long-term potentiation and depression. This plasticity is vital for encoding and retaining information adaptively, mirroring the

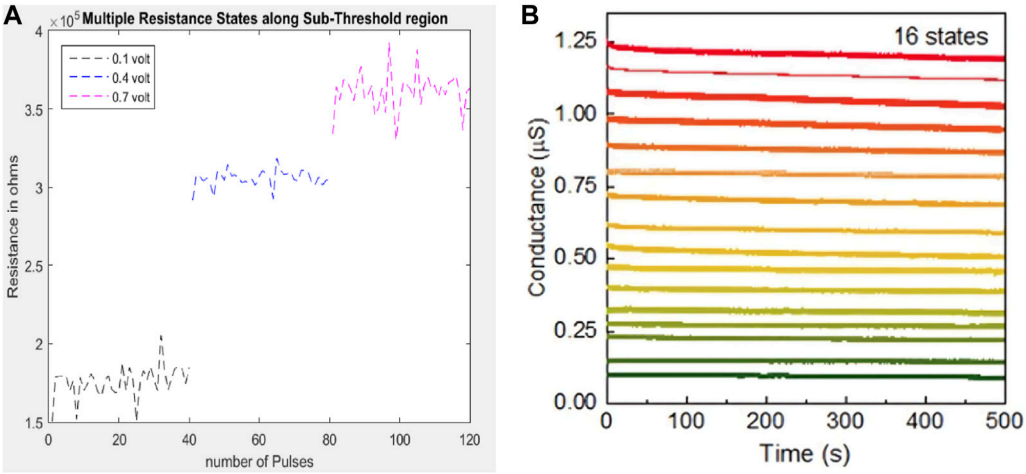

FIGURE 4
(A) Multiple resistance levels along the sub-threshold region within a 7.5 um² memristor device at room temperature (Zaman et al., 2017). **(B)** Retention performance of 4-bit distinguishable intermediate states of a $LiNbO_3$ memristor (Wang et al., 2023a).

cognitive capabilities of the human brain. Additionally, Tong et al. (2021) explore the intersection of optoelectronics and synaptic behavior in $LiNbO_3$, implying that optoelectronic modulation can enhance the synaptic plasticity of $LiNbO_3$-based devices. The ability to manipulate synaptic weights through light-induced processes opens avenues for innovative neuromorphic computing architectures, allowing for dynamic and flexible adaptation under varying conditions. Some studies are based on non-volatile synaptic characteristics and high-precision memory recognition based on lithium niobate. For instance (Wang et al., 2023b), emphasize the role of $LiNbO_3$ in achieving stable and precise synaptic weight updates. The high-speed switching dynamics of $LiNbO_3$ contribute to the efficiency of weight update operations, a crucial element for the overall performance of neuromorphic systems.

Multi-level resistance states and weighted synapses

$LiNbO_3$ memristors play a significant role in achieving multi-level resistance states and weighted synapses within neuromorphic computing. $LiNbO_3$-based memristors exhibit multi-level resistance states, enabling the implementation of weighted synapses. This aspect, discussed by (Zaman et al., 2017), is pivotal for the precision and flexibility of synaptic emulation. The ability to represent the strength of connections between artificial neurons with high granularity enhances neuromorphic systems' computational power and accuracy. $LiNbO_3$-based memristors exhibit multi-level resistance states, providing the opportunity for implementing weighted synapses. This feature is essential for accurately representing the strength of connections between artificial neurons in a neuromorphic system (Zaman et al., 2017; Zaman, 2020). Multi-level resistance states contribute to the precision and versatility of synaptic emulation.

Figure 4A shows experimental findings concerning the stability challenges influencing the non-volatile $LiNbO_3$ circuit element at room temperature. The plot in Figure 4A illustrates a steady rise in resistance levels and the stability of the state for voltage pulses at 0.1, 0.4, and 0.7 V. Stable resistance states between the high and low resistance states of the Ti/$LiNbO_3$/Pt MIM structure were successfully attained for the three distinct pulse voltages. Besides, Figure 4B confirms the $LiNbO_3$ memristor's high reliability across multiple conductance levels (16 distinguishable states) for weight updating in artificial neural networks (Wang et al., 2023b).

Zaman (2020) and Morozov et al. (2022) delve into the precision of synaptic weight representation achievable with $LiNbO_3$-based memristors. These studies imply how the multi-level resistance states of $LiNbO_3$ allow for a fine-grained and continuous adjustment of synaptic weights. This precision is essential for accurately mimicking the diverse strengths of synaptic connections observed in biological neural networks. Zaman (2020) also contributes to the discourse by showcasing the versatility of $LiNbO_3$-based memristors in creating weighted synapses for various neuromorphic tasks, emphasizing the precision of $LiNbO_3$ in representing synaptic weights and demonstrating its applicability across a spectrum of neuromorphic computing applications. This versatility positions $LiNbO_3$ as a material capable of meeting the diverse requirements of artificial neural networks.

Zaman et al. (2020) provide experimental evidence supporting the feasibility of achieving weighted synapses with $LiNbO_3$-based memristors. Experimental studies also reveal how $LiNbO_3$'s inherent properties, when harnessed through advanced fabrication techniques, enable the reliable and reproducible creation of memristors with multiple resistance states (Wang et al., 2017; Zaman et al., 2019). These experimental validations reinforce the theoretical foundation for $LiNbO_3$ as a material for implementing weighted synapses. Besides, Wang et al. (2017) explore the role of weighted synapses in enabling dynamic adaptation within neuromorphic systems. Their research demonstrates how the precise adjustment of synaptic weights, facilitated by $LiNbO_3$'s multi-level resistance states, contributes to the efficient emulation of cognitive functions such as pattern recognition and deep learning capabilities. This dynamic adaptation is a hallmark of intelligent systems inspired by biological neural networks.

Expanding on the scalability (Saleh and Koldehofe, 2022) of $LiNbO_3$-based memristors, Pan et al. (2019) and Wang et al. (2017) investigate how the material can be integrated into large-scale neuromorphic architectures. These studies emphasize that $LiNbO_3$'s multi-level resistance states and compatibility with advanced fabrication techniques make it a promising candidate for building complex neural networks. This scalability is crucial for realizing sophisticated neuromorphic systems that can tackle increasingly complex cognitive tasks. As this field progresses, the integration of $LiNbO_3$ into neuromorphic architectures holds the promise of creating highly adaptive, precise, and efficient artificial intelligence systems.

Electro-optic and nonlinear optical properties

$LiNbO_3$'s electro-optic and nonlinear optical properties add a layer of versatility to its utility in neuromorphic computing. Studies have extensively explored these properties, highlighting how $LiNbO_3$ facilitates various nonlinear optical processes, including frequency conversion and generation of new wavelengths through processes like second harmonic generation. Abdul-Hussein and Almusawe (2023) emphasize how electro-optic and nonlinear optical properties can be harnessed to create efficient optoelectronic synapses, paving the way for innovative neuromorphic devices. They further show that the effect of doping by Mo improves optical properties, such as the material's absorption spectrum. It also increases the effect of second harmonic generation, a fundamental prerequisite for designing optical devices in many photonic applications (Cabuk, 2012; Abdul-Hussein and Almusawe, 2023). Doping with MgO can also enhance the electro-optic coefficient (Kang et al., 2006). Combining electro-optic effects and nonlinear responses in $LiNbO_3$ expands the possibilities for developing advanced neuromorphic architectures.

Foundational works by Weigand et al. (2021), Chen et al. (2021b), and Xu et al. (2022) delve into the electro-optic effect in $LiNbO_3$, emphasizing its role in light modulation. This property allows precise refractive index control response to an applied electric field, making $LiNbO_3$ a cornerstone in developing electro-optic modulators for optical communication systems (Weiss et al., 2022). Additionally, experimental studies have expanded the discourse by exploring electro-optic tuning in resonant photonic devices. Research demonstrates how $LiNbO_3$'s electro-optic properties can be harnessed to dynamically tune the resonance in micro-resonators and photonic circuits, offering a pathway toward reconfigurable and adaptive optical systems (Witmer et al., 2017; Boes et al., 2018; Lin et al., 2020). Periodically poled lithium niobate (PPLN) photonic wires have also shown potential for developing a wide range of nonlinear wavelength converters and devices for all-optical signal processing (Hu et al., 2009; Poberaj et al., 2012).

Eid et al. (2020), Pan et al. (2021), and Minakata (2001) discuss the applications of $LiNbO_3$ high-speed modulators in optical communication systems, highlighting the intrinsic advantages of $LiNbO_3$ in achieving gigahertz-speed modulation, a crucial factor in the development of high-performance optical communication networks. Zheng and Chen (2021) shift focus to parametric processes enabled by $LiNbO_3$, particularly four-wave mixing. The nonlinear response of LiNbO3 is exploited for generating new frequencies through the interaction of intense optical waves, a phenomenon crucial for applications in wavelength conversion and signal processing (Liu et al., 2019). Likewise, Zeng et al. (2008), Lefort et al. (1999), Bache and Wise (2010), Hu et al. (2012), and Yu et al. (2022) investigate the ultrafast nonlinear optical properties of $LiNbO_3$. These studies highlight the potential of $LiNbO_3$ in ultrafast pulse compression, an essential capability for applications in telecommunications, and the generation of ultrashort laser pulses. Sang et al. (2006), Zhao et al. (2020), Jin et al. (2014), and Suhara (2009) delve into the potential of $LiNbO_3$ in generating entangled photon pairs through nonlinear processes, showcasing its relevance in the burgeoning field of quantum optics. Finally, Wei et al. (2018) and Sun et al. (2020) demonstrate how integrating $LiNbO_3$ into photonic crystal structures enhances nonlinearities, paving the way for compact and efficient nonlinear photonic devices. Collectively synthesizing multiple findings reveals LiNbO3's richness in electro-optic and nonlinear optical properties. From high-speed modulators to quantum information processing, $LiNbO_3$'s diverse capabilities in photonics make it an important material in advancing optical communication and signal processing technologies.

Volatile properties of LiNbO3 memristors

Dynamic memristors based on $LiNbO_3$ exhibit unique volatile properties, primarily attributed to its nonlinear I-V (current-voltage) characteristics. As shown in Figure 5, $LiNbO_3$ device exhibits bi-directional switching between a HRS and a LRS when the voltage surpasses specific threshold values of either polarity. Once the voltage intensity decreases below a certain hold value, spontaneous transition from LRS to HRS occurs, indicating the device's volatile memristive behavior. Besides, its I-V characteristics display nonlinearity, regardless of varying sizes, signifying volatile switching across all lithium niobate devices. Despite size differences, all devices switch to LRS at approximately 2 V. Additionally, Figure 5F illustrates the dependency of LRS and HRS currents on device size, where HRS current escalates with device size while LRS current remains relatively constant. This suggests a filamentary nature in volatile switching. The I-V curves in Figure 5F for a specific device size under positive voltage sweepings with different stop voltages reveal an increase in LRS current with higher stop voltages, indicating thicker conducting filament formation under stronger voltages. The nonlinearity in the I-V curve enables the memristor to have short-term memory, a characteristic that sets it apart from traditional resistive switching devices (Zhao et al., 2023).

The volatile property stems from the material's ability to undergo reversible changes in resistance, enabling swift information storage and retrieval within short time frames (Hu et al., 2021). This short-term memory effect indicates that the device's resistance state can be altered temporarily, making it suitable for applications where dynamic or volatile memory is desirable, including reservoir computing and domain wall random access memory (Hu et al., 2021; Wang et al., 2023a; Zhao et al., 2023). Hence, the short-term memory capabilities of lithium niobate memristors make these devices suitable for neuromorphic computing.

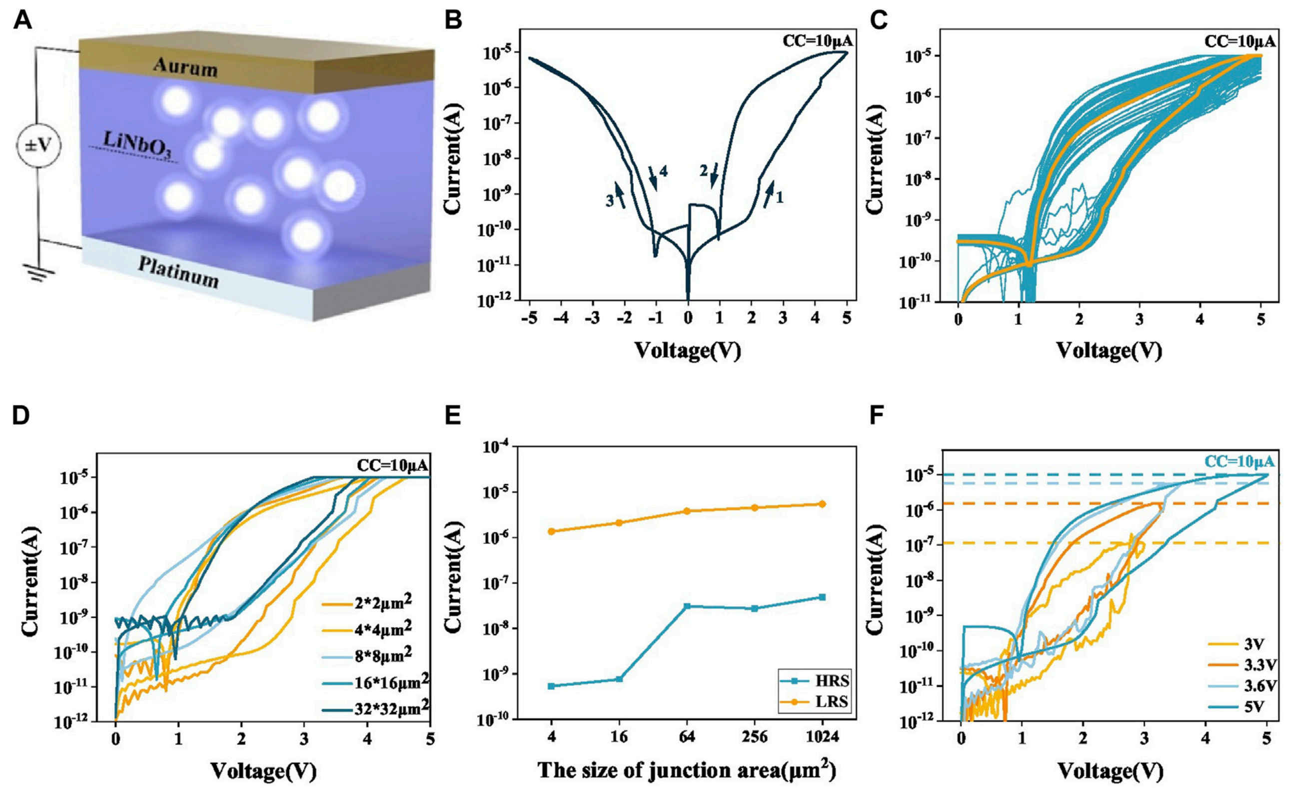

FIGURE 5
(A) shows the schematic structure of the Pt/$LiNbO_3$/Au memristor, while **(B)** illustrates the typical I-V characteristics of the lithium niobate memristor. **(C)** displays the results of a fifty-cycle endurance test conducted on the lithium niobate memristor. **(D)** presents the I-V characteristics of five lithium niobate memristors of varying sizes. **(E)** shows the currents flowing through five lithium niobate memristors of different sizes in both their low resistance states and high resistance states. **(F)** exhibits the I-V characteristics obtained by altering the stop voltage during the sweeping process (Zhao et al., 2023).

Compatibility with advanced fabrication techniques

The seamless integration of novel materials into neuromorphic devices necessitates compatibility with advanced fabrication techniques. $LiNbO_3$ aligns with this requirement, enabling precise manufacturing processes and contributing to developing high-performance neuromorphic devices. Advancements in fabrication techniques have facilitated the integration of $LiNbO_3$ into memristor arrays. The compatibility of $LiNbO_3$ with various fabrication methods, such as chemical vapor deposition and sputtering (Marković et al., 2020; Liang et al., 2021; Wang et al., 2023a) ensures scalable and reproducible production of memristor devices for potential large-scale neuromorphic computing applications (Bornand et al., 2003; Uchino, 2017). Additionally, the advancements in lithography and etching techniques directly influence the properties of the underlying LNOI material. Lin et al. (2020) and Qi and Li (2020) provide insights into the compatibility of $LiNbO_3$ with photonic lithography techniques. Likewise, the focused ion beam (FIB) lithography technique has great potential to precisely, etch $LiNbO_3$ thin films (Chen et al., 2020; Jia et al., 2021; Leng et al., 2024). Such studies demonstrate that $LiNbO_3$-based structures can be precisely patterned at the submicron scale, which can allow for the creation of intricate neuromorphic circuits. This compatibility with advanced fabrication techniques opens avenues for the development of densely packed and intricately designed neural networks, crucial for enhancing computational efficiency.

Besides, integrating electro-optic devices on lithium-niobate-on-insulator (LNOI) holds promise for enhancing the functionality and performance of memristors in neuromorphic systems. LNOI has an edge over indium phosphorus, silicon, silicon nitride, and silicon oxide materials due to multiple features such as intrinsic electro-optical effects, which makes LNOI's optical switching speed faster with lower power consumption than its counterparts that depend on thermal-optical effects to attain the modulation of optical phase (Hu et al., 2012; Yuan et al., 2021). Likewise, LNOI combines the exceptional electro-optic properties of lithium niobate with the advantages of an insulating layer, enhancing the performance of photonic devices. Boes et al. (2018), Lin et al. (2020), and Saravi et al. (2021) explore the fabrication technology and applications of photonic structures on LNOI. Incorporating photonic structures on LNOI platforms thus opens avenues for developing compact, energy-efficient, and high-performance photonic devices with implications for telecommunications, sensing, and quantum technologies. Likewise, Lewis et al. (2012) shed light on using nanoimprint lithography for $LiNbO_3$-based devices. Nanoimprint lithography, known for its high-throughput capabilities, is compatible with $LiNbO_3$, allowing for the rapid and cost-effective fabrication of neuromorphic components. This compatibility is pivotal for the large-scale manufacturing of neuromorphic devices, a crucial step towards the practical implementation of $LiNbO_3$ in neuromorphic computing and artificial intelligence systems.

Studies have demonstrated the compatibility of $LiNbO_3$ with advanced fabrication techniques. This adaptability positions $LiNbO_3$ as a versatile material that can be seamlessly integrated into the rapidly evolving landscape of neuromorphic device manufacturing, presenting a potential for developing precise, scalable, and multifunctional artificial intelligence systems. The intricate interplay between advanced fabrication methods and the unique characteristics of $LiNbO_3$ memristor devices opens avenues for tailoring neuromorphic devices with unprecedented precision, paving the way for their seamless integration into the rapidly evolving landscape of artificial intelligence and cognitive computing.

Conclusion

The significance of lithium niobate memristors in neuromorphic computing and its potential impact on artificial intelligence applications cannot be ignored. The literature reviewed reveals the unique properties of $LiNbO_3$ that make it an excellent candidate for neuromorphic computing. Its unique set of electro-optic and nonlinear optical properties, non-volatile nature, low power consumption, high-speed switching, multi-level resistance states, I-V volatile properties, and compatibility with advanced fabrication techniques position $LiNbO_3$ as a versatile material for efficient and high-performance memristor-based neuromorphic systems. As the field advances, integrating $LiNbO_3$ into neuromorphic architectures holds immense promise for realizing dynamic, responsive, and efficient artificial intelligence systems.

Author contributions

CK: Resources, Writing–original draft, Writing–review and editing. YL: Resources, Supervision, Writing–review and editing, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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