Fabrication and Experimental Setup for Neuromorphic Memory Devices: Performance Characterization of Neuron-Like Fibers

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***Abstract*: To recreate the synaptic plasticity mechanisms of biological brain networks in artificial devices, the area of neuromorphic computing has become crucial. Creating memory devices based on polymers, such as Polyvinyl Acetate (PVAc), doped with metal ions to simulate long-term depression (LTD) and long-term potentiation (LTP), is one potential trend. The optimization of device performance to guarantee stability and dependability under extended load is still a challenge, despite notable developments. By employing the use of I-V characterizations and pulse stress tests, this study assesses the ability of PVAc (+ metal ions) fiber devices to mimic neuromorphic memory functioning. Stress voltages of ±6V and ±15V were applied to the manufactured devices over 100 cycles, with a 10-second stress time and a 10-ms delay. Maximum current, current-voltage response and plasticity were examined. The findings show that the PVAc (+ metal ions) devices showed gradual increases in current under repeated cycles and notable synaptic-like plasticity over the first 300 seconds of stress application. Nevertheless, a saturation point was noted, which prevented more plasticity increase. The devices demonstrated strong performance over a range of voltages, but they also made clear the necessity for optimization to strike a compromise between neuromorphic imitation and device longevity. This study concludes by showing that PVAc (+ metal ions) has the potential to be a good option for neuromorphic memory applications, highlighting the significance of endurance optimization and operational restrictions in subsequent designs.**

***Keywords*: Neuromorphic, Polyvinyl acetate, Memory device, Metal ion, Plasticity.**

1. Introduction

Neuromorphic computing, which is based on how the human brain works, shows a major change in computing technology and opens new opportunities for advances [1]. The brain's parallel and energy-efficient processing capabilities are targeted to be emulated by neuromorphic systems, unlike customary computing systems that rely on sequential processing [2]. The human brain contains approximately 86 billion neurons and makes an average of trillions of synaptic connections [3]. What is impressive is the efficiency with which it functions, since it only requires around 20 watts to operate [4]. This is in complete contrast to traditional computing systems which require huge amounts of energy to deliver even a fraction of such capabilities. This gap has led to the Skunkworks trying to devise system architectures based on neural processing which has brought about neuromorphic computing. The development of many memory devices sits at the heart of this innovation, as they mimic the behavior of biological neurons, and synapses, which allows for multiple advanced cognitive functions like learning, memory retention, and decision-making [5].

These systems rely on neuromorphic memory devices to process and store information, and they play an important role in their function. Unlike customary memory devices such as Dynamic random-access memory (DRAMS), Static random-access memory (SRAM), and flash memory, which work well for regular tasks, neural processes require a type of dynamic adaptability that these devices simply do not possess [2]. The growing interest in exploring and developing neuron-like materials, and architectures that mimic important neural behaviors, such as synaptic plasticity, spiking, and self-

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organization, has emerged and one promising approach in this area involves using neuron-like fibers that is objective to imitate the structure, and function of biological neurons. These fibers contain special materials. They have special electrical and ionic properties. These features can help connect biological and artificial systems. The production of neuron-like fibers necessitates advanced technologies that facilitate the required accuracy of their diameter, composition, and structure with the needed level of homogeneity [6]. Fibers with nanoscale elements that improve their efficacy have been produced using techniques such as electrospinning, thin film deposition, and nanofabrication. These processes of fiber construction are crucial because they enable the fibers to efficiently reproduce the non-linear and adaptive properties of biological neurons. However, the practical realization of such fibers remains a significant barrier, requiring novelty in material science, fabrication technique, and device integration. Therefore, this research aims at fabricating and characterizing neuron-like fibers as a foundational component of neuromorphic memory devices.

2. Materials and Methods

Research Design: This study used an experimental study design to compare the performance of a fabricated memory device to an established neuromorphic memory model. The devices were assessed by characterizing electrical responses under various conditions for their ability to recreate some aspects of neuromorphic behaviors. The study observes the ethical protocol as it does not have human or animal subjects. Data was collected through the measurement of electrical performance metrics of the fabricated devices, especially the current-voltage relationship. The results were then analyzed to ascertain the level of key neuromorphic characteristics exhibited by the devices such as plasticity, hysteresis, and spiking behavior. Benchmarking against standard neuromorphic metrics was done to check the capacity of the devices to show the expected behaviors.

Equipment: Some equipment used include; Glass substrates, tweezers, and spin coating machines for precise fabrication., EM Shielded Probe Station and Pico-ammeter for electrical characterization, Spin cup, Vacuum Evaporator, Shadow mask, Nitrogen gun, Microscope, Fume hood.

Validation Steps: The first validation step was defining the target neuromorphic behaviors which included; i-Plasticity: The potential for the device to alter the strength of a synapse in reaction to signals, modeled after neurobiological processes of learning. ii-Hysteresis: The dependence of the device's output on the current input as well as the previous inputs, which is necessary for reproducing the spiking behavior of neurons. The second step was the fabrication of the device: Two categories of devices were deposited on glass substrates using thermal evaporation and shadow mask patterning; reference devices: formed aluminum gap cells with Polyvinyl Acetate (PVAc) coating. Devices with Metal Ions- the devices are the same as the reference devices but the difference is that metal ions are added into the solution of PVAc because they are expected to affect the neuromorphic behavior of the devices.

Fabrication Step: The first step for fabrication was the cleaning of the substrate, the glass substrates were cleaned with nitrogen gas for impurity removal. Aluminum thin films of 200 nm thickness were deposited on glass substrates through vacuum thermal evaporation using a shadow mask for patterning (as shown in Figure 1). Solutions involving the dissolution of PVAC in methanol or ethanol and metallic ions were prepared for the film casting and spin coating processes to prepare fibers about neuron morphologies that can be used in device construction. A solution was prepared by accurately measuring 300 mg of Polyvinyl acetate (PVAc) using an analytical balance and dissolving it in 3 ml of methanol. The mixture was placed in an ultrasonic bath machine and shaken to ensure complete dispersion of the PVAc in the solvent. This solution was then employed to deposit a thin PVAc film onto a substrate by drop-casting it with a syringe, followed by spinning the fabricated cup at a speed ranging between 5,000 and 10,000 RPM. The spin coating cup, a key component in fabricating PVAc fibers for this study, is constructed from aluminum, weighs approximately 17.5 g, and is designed to fit onto the rotor of the spin coating machine.

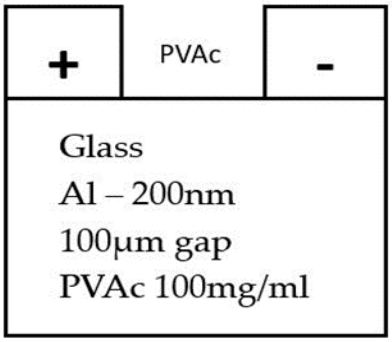

Fig.1: Schematics of the fabricated device on a glass substrate.
Source: Researchers Fieldwork, 2023

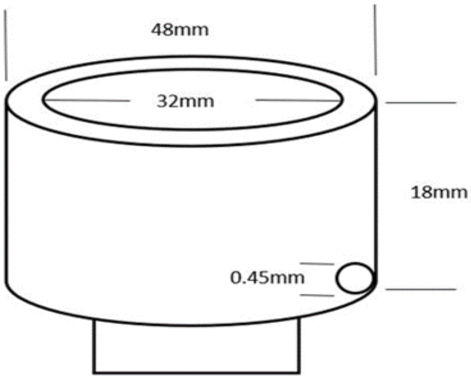

Fig. 2: Schematics of the spin coating cup.
Source: Researchers Fieldwork, 2023

When the PVAc solution is introduced into the cup, it spins at a high rotational speed of 9,000 RPM, expelling fibers through a small outlet located at the base (refer to Figure 2). The resulting film is subsequently annealed to remove any residual solvent and enhance the adhesion of PVAc to the substrate. Methanol is critical in preparing the PVAc solution, as it ensures complete dissolution of the polymer and even distribution within the mixture.

Device Characterization: During the experiments, the devices were subjected to I-V (current-voltage) characterization to assess their electrical properties which involved the current affinity of the considered devices. This was carried out in the Electron microscope (EM) shielded probe station using the pico-ammeter with a voltage source. Both the simple I-V and Pulse Stress I-V characterization were performed on the devices (the setup is shown in figure 3). The simple I-V characterization was conducted in 100 cycles of sweeping voltage across the devices ranging from -5V to +5V. For Pulse Stress I-V Characterization, the specific voltages were stressed on the devices for several cycles after every 100 wait times to analyze the performance of the devices.

Neuromorphic Behavior Testing: The performance characteristics of the devices were characterized by relative changes in conductance according to the applied voltage and current inputs: changes in conductance and capacitance; synaptic plasticity modes including spike-timing-dependent plasticity (STDP).

Data Exploration and Comparison: The collected data were categorized into reference and test groups (with metal ions). The device metrics were compared to biological synaptic benchmarks, analyzing patterns for neuromorphic mimicry. The Agilent VEE Software was used for data acquisition and analysis.

Fig. 3: Device characterization set-up.
Source: Researchers Fieldwork, 2023

3. Result and Discussion

This section explains the result of the experimental setup, an effective way of justifying if a certain class of memory device mimics neuromorphic memory is to test and observe them for properties of term potentiation (LTP) and long-term depression (LTD). LTP) and LTD occur due to synaptic plasticity mechanism that has a strong association with learning and memory. LTP follows immediately after a brief electrical stimulation whereby synapses are strengthened while LTD follows the activity of the neuron (or pulse stress) and synapses are weakened.

Metal ions were incorporated into the Polyvinyl Acetate (PVAc) fiber device used in this study to adjust its electrical properties under electrical stimulation, simulating the function of metal ions in biological synapses.

A. *Simple I-V PVAc (+ metal ions) Characteristics*

Figure 4 below shows the simple I-V characteristics of the fabricated PVAc (+ metal ion) sample device. A voltage scan that begins from -5 volts to plus 5 volts delving into for 10ms period. Such reversal provided an interesting aspect of analysing the voltage drive of the device as the both negative and positive voltage was applied. When these different polarities were compared, -5V was seen to have a lower current of -122 PA compared to the 14 PA recorded at +5110 PA. The graph depicts a rapidly increasing current with the application of a negative voltage with very little variation when a positive voltage is applied. A measurement system has been clearly shown where all the devices on the panel are ideal and allow only limited current. The rectification properties present within the device imply the conduction mechanism employed is polarized based on the interaction between the metal ions and the polymer matrix.

Devices such as PVAc and PEDOT: PSS poly (3,4-ethylene dioxythiophene) (PEDOT) and polystyrene sulfonate (PSS) that are doped with ions have shown polarisation with the ionic migration and traps due to interfaces [7]. Lee and Jeong (2024) elucidated that ionic polarization that arises within the polymer modifies the function of the device in neuromorphic applications. These results also correspond with those specific findings strengthening the assumption that metal ions facilitate synaptic-like behaviours in memory devices [10]. Theoretically, the sharp increase in the current observed at negative voltage indicates that there was an enhancement in the mobility of the charge carriers due to ion migration [8]. A similar phenomenon can be observed in calcium and sodium ion biological synapses, which adjust the amplitude of synapses by varying the voltage of membranes [6].

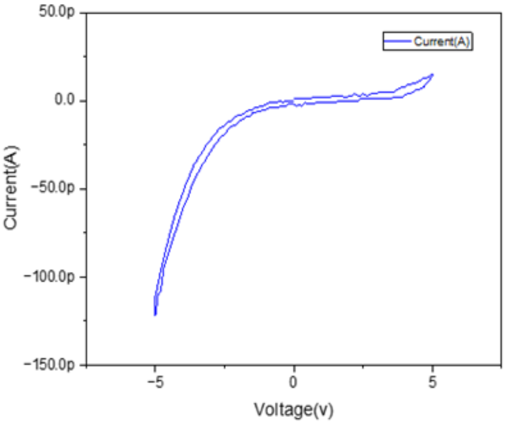

Fig.4: Simple I-V PVAc Characteristics Curve
Source: Researchers Fieldwork, 2023

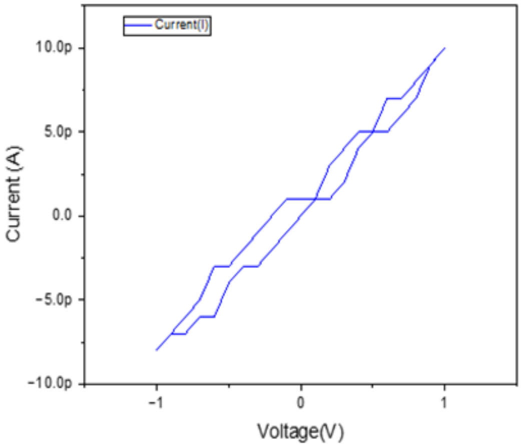

Fig. 5: Simple I-V of PVAc Fiber (+ Metal Ions) from -1v t0 +1v
Source: Researchers Fieldwork, 2023

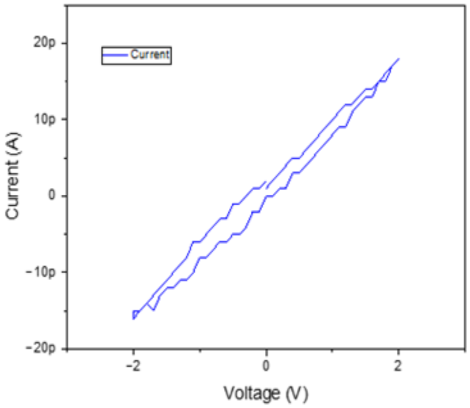

Fig. 6: Simple I-V of PVAc Fiber (+ Metal Ions) from -2v t0 +2v
Source: Researchers Fieldwork, 2023

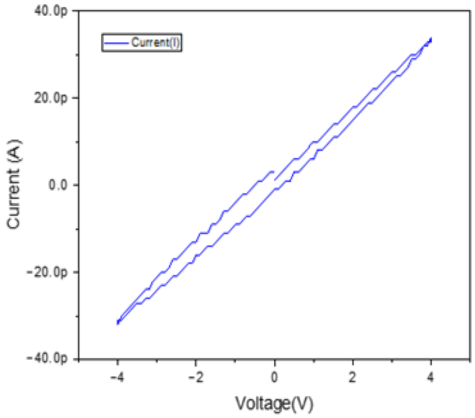

Fig. 7: Simple I-V of PVAc Fiber (+ Metal Ions) from -4v t0 +4v
Source: Researchers Fieldwork, 2023

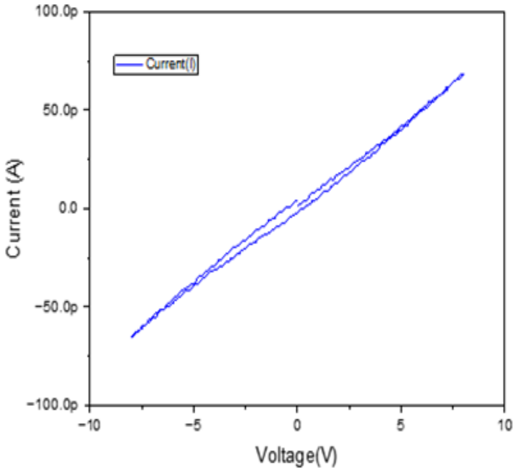

Fig. 8: Simple I-V of PVAc Fiber (+ Metal Ions) from -8v t0 +8v
Source: Researchers Fieldwork, 2023

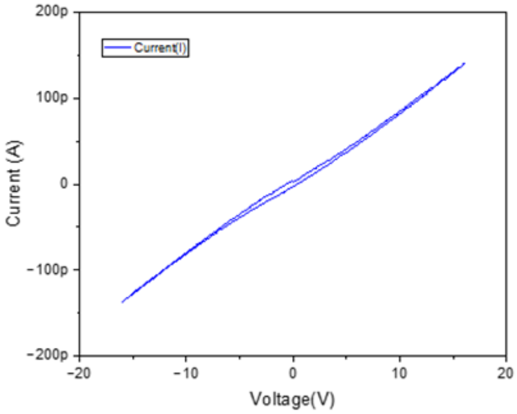

Fig. 9: Simple I-V of PVAc Fiber (+ Metal Ions) from -16v t0 +16v
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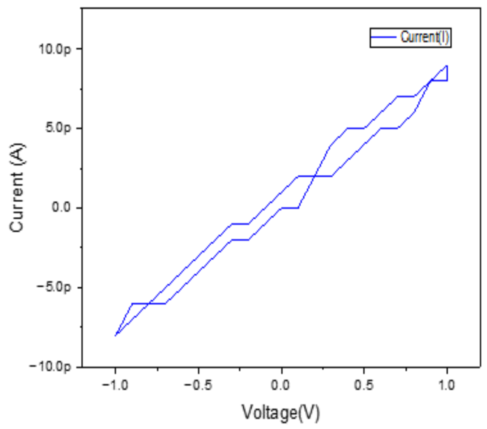

Fig. 10: Simple I-V of PVAc Fiber (+ Metal Ions) from -1v to +1v
Source: Researchers Fieldwork, 2023

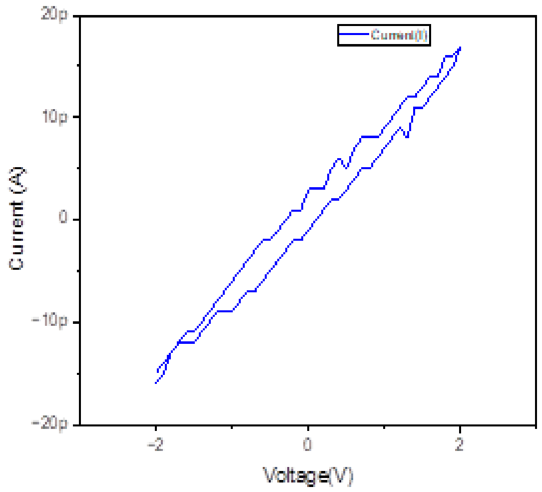

Fig. 11: Simple I-V of PVAc Fiber (+ Metal Ions) from -2v to +2v
Source: Researchers Fieldwork, 2023

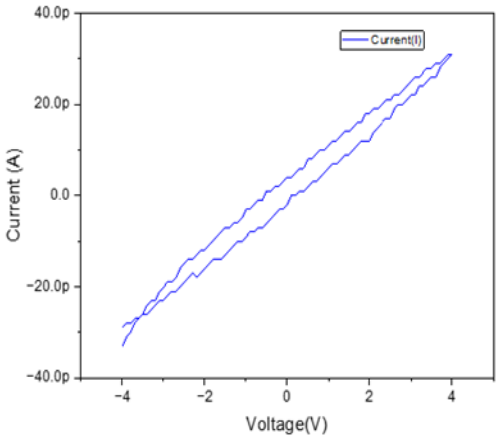

Fig. 12: Simple I-V of PVAc Fiber (+ Metal Ions) from -4v to +4v
Source: Researchers Fieldwork, 2023

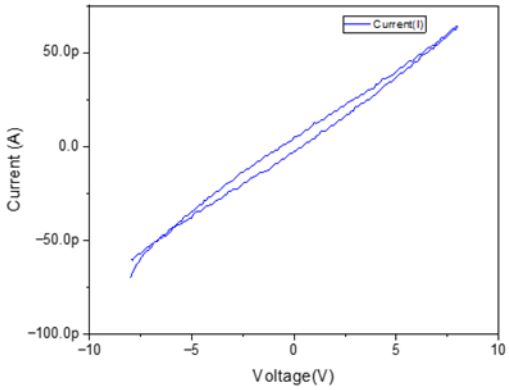

Fig. 13: Simple I-V of PVAc Fiber (+ Metal Ions) from -8v to +8v
Source: Researchers Fieldwork, 2023

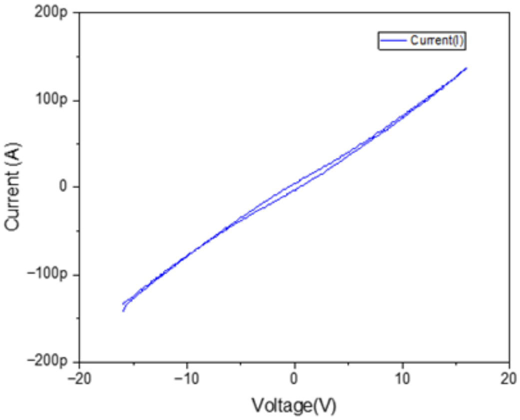

Fig. 14: Simple I-V of PVAc Fiber (+ Metal Ions) from -16v to +16v
Source: Researchers Fieldwork, 2023

Figures 5 to 14 demonstrate that the fabricated fiber device, enhanced with metal ions, maintained stable functionality across all tested voltages and initial conditions without any signs of breakdown. This stability validated the device's reliability, allowing us to proceed with the pulse stress tests for further analysis.

B. Pulse Stress I-V PVAc (+ metal ions) Characteristics:

To determine their performance characteristics, a mechanical evaluation of the two fabricated devices was conducted through stress testing. Each device was subjected to the stress voltage of +6V and -6V, separated by 10ms waiting time and a stress application period of ten seconds each. The selection of the stress voltage of 6V concurs with the limits under which memory devices can safely operate and is also in line with the result of the earlier I-V characterization carried out between -5 and +5. A total of 100 pulse stress cycles were performed to test the electrical response of the device under repetitive induced voltage stress for stability and endurance evaluation of the device. The following is a step-by-step process of the pulse stress test applied to PVAc (with metal ions), device 1.

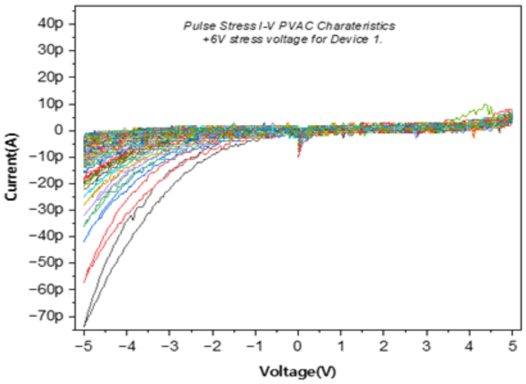

Fig. 15: Pulse Stress I-V PVAc Characteristics Curve for Device 1.

Source: Researchers Fieldwork, 2023

C. *Pulse Stress I-V Characteristics Curve for Device 1*

The I-V characterization presented above begins at 0V and displays the response across 100 cycles of continuous stress applied to Device 1. During the test, the device was subjected to a constant stress of +6V with a delay time of 10 ms, while voltage sweeps ranged from -5V to +5V. The resulting curves reveal distinct changes across the cycles. Notably, with each successive cycle, the current response improves significantly under the application of negative voltage. In contrast, no substantial variation is observed on the positive side of the plot. The enhanced current response during the negative voltage application highlights a cycle-dependent behavior of the device. Further analysis of the plot provides deeper insights into the mechanisms underlying the observed trends, as detailed below;

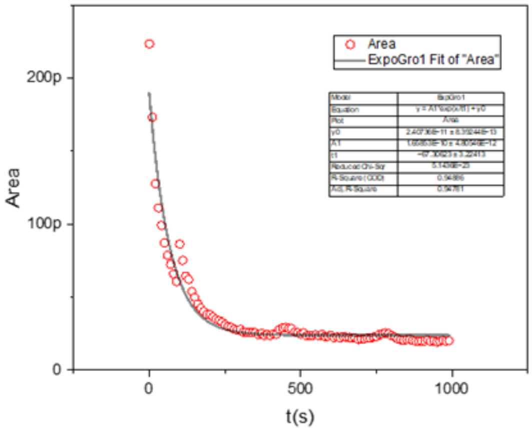

Fig. 16: Area plot of the Pulse Stress I-V PVAc Characteristics Curve for Device 1.

Source: Researchers Fieldwork, 2023

Figure 16 presents the area-versus-time plot derived from the pulse stress characteristics curve of device 1, as previously shown in Figure 15. The absolute area under each curve in Figure 15 was calculated and plotted against the corresponding stress time. To provide a clearer understanding of the device's plasticity performance, a fitted curve was applied to better represent this behavior. In Figure 17, the maximum current (Imax) from each cycle in Figure 15 is plotted against time, with a fitted curve also employed to evaluate the device's performance over time.

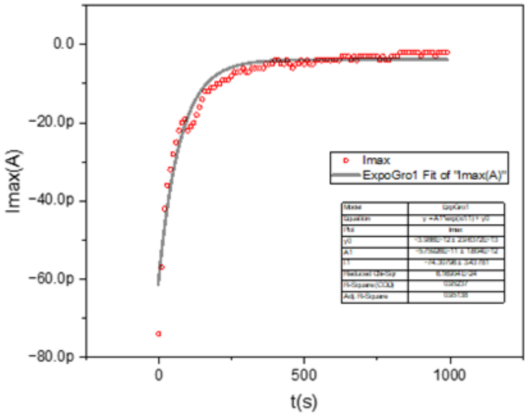

Fig.17: Maximum current (Imax) plot of the Pulse Stress I-V PVAc Characteristics Curve for Device 1.

Source: Researchers Fieldwork, 2023

The curve demonstrates a consistent variation in the maximum current (Imax) throughout the application of the stress voltage, persisting until approximately 300 seconds. Beyond this point, no notable changes in Imax were observed, indicating that the device reached a stable state under the applied stress. To evaluate plasticity, characterized by changes in ImaxI_{\text{max}}Imax as a function of time or cycles, a first-order differentiation was performed on the fitted curve. This analysis provided additional insights, with the results presented in Figure 18 below.

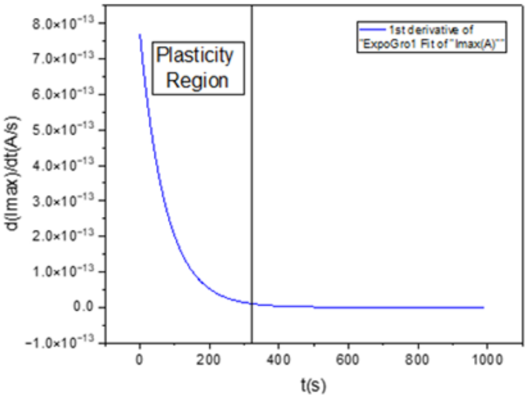

Fig. 18: Plasticity Region.

Source: Researchers Fieldwork, 2023

Figure 18 depicts the differentiated curve derived from the fitted data of the previous analysis, effectively emphasizing the plasticity region of the device. The plot reveals that beyond 300 seconds, no significant changes are observed, signifying the end of noticeable plasticity behavior. Plasticity, being a vital attribute for assessing a device's potential to mimic neuromorphic memory, establishes 300 seconds as the operational limit for the device's plasticity performance. This threshold is crucial for evaluating the suitability of the device for neuromorphic applications.

The tests indicated that there were gradual shifts in the values of maximum current irrespective of whether the components were tested at voltages of plus and minus 6 volts or plus and minus 15 volts after every 100 cycles. Experiments carried out after a time frame of about five minutes were able to exhibit significant plastic deformation. The maximum current graph delineated a curve that suggested a plateau region below the –0.8 mA which indicated that there was a degree of plastic deformation that could be utilized with the device. The device's internal wiring exhibits an increased amount of strengthening after enduring several cycles of stress – this action replicating a biological mechanical phenomenon. Bag et al. (2024) noted that similar plasticity happenings were also demonstrated in RRAM (Resistive random-access memory) devices whereby conductivity alterations elicited by ionic migration resembled LTP/LTD. This study in the context of LTP/LTD produced by polarization of ionic conduction membranes reinforces the idea that PVAc-based devices have good prospects for neuromorphic systems application in LTP/LTD [9].

The device characterization was extended by applying a voltage range of -10V to +10V, coupled with a pulse stress of +15V and -15V, with a 10-second stress delay between applications. This test was performed twice to evaluate the device's performance under two variations: starting at 0V and starting at a specific voltage. These variations provided a more comprehensive understanding of the device's response to different starting conditions.

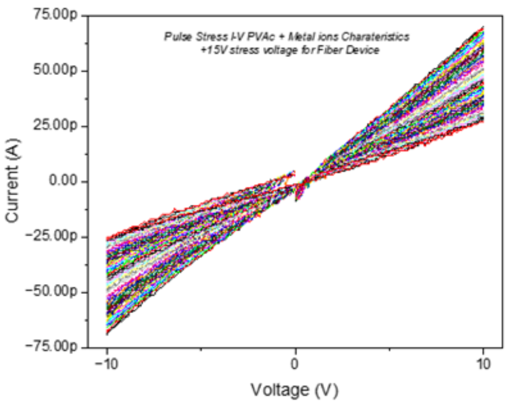

Fig. 19: Pulse Stress I-V PVAc (+ metal ion) Characteristics Curve for Fiber Device1 (Pulse Stress of +15V)
Source: Researchers Fieldwork, 2023

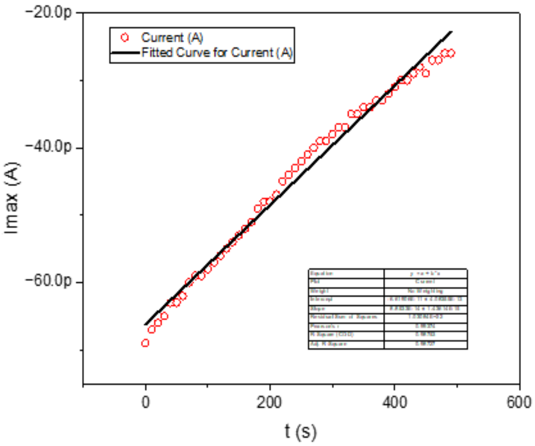

Fig.20: Maximum current (Imax) plot of the Pulse Stress I-V Characteristics Curve
Source: Researchers Fieldwork, 2023

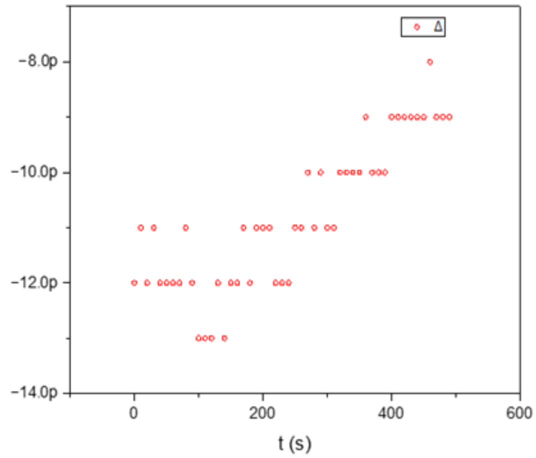

Fig. 21: Shift plot of the Pulse Stress I-V Characteristics Curve
Source: Researchers Fieldwork, 2023

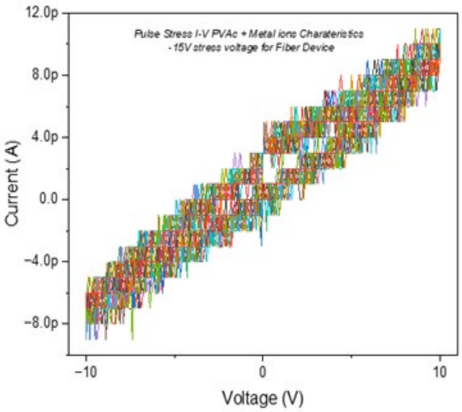

Fig. 22: Pulse Stress I-V PVAc (+ metal ion) Characteristics Curve for Fiber Device
Source: Researchers Fieldwork, 2023

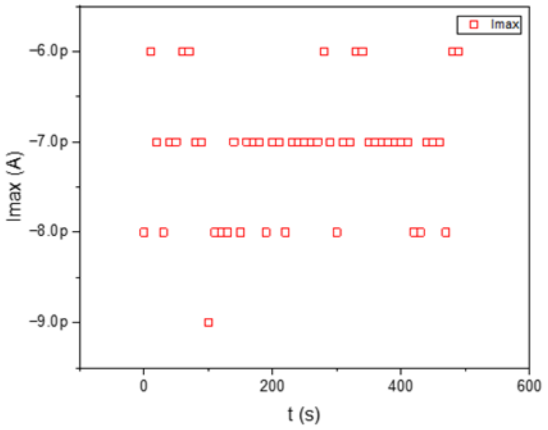

Fig. 23: Maximum current (Imax) plot of the Pulse Stress I-V PVAc Characteristics.
Source: Researchers Fieldwork, 2023

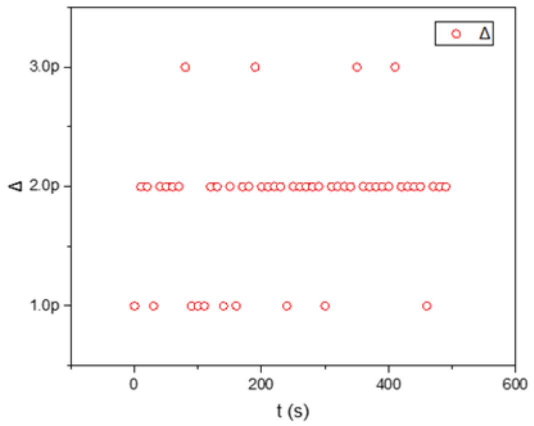

Fig. 24: Shift plot of the Pulse Stress I-V Characteristics Curve
Source: Researchers Fieldwork, 2023

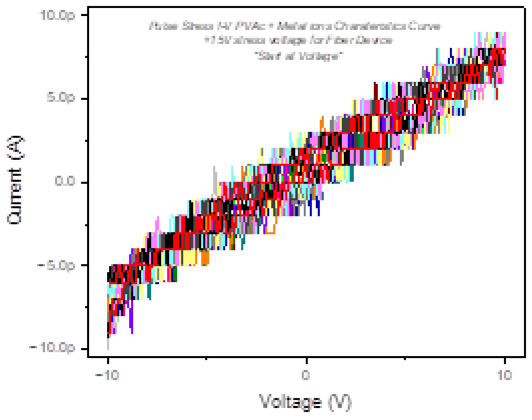

Fig. 25: Pulse Stress I-V PVAc (+ metal ion) Characteristics Curve for Fiber Device
Source: Researchers Fieldwork, 2023

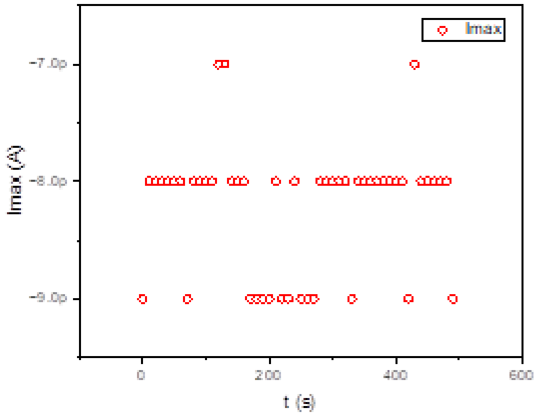

Fig. 26: Maximum current (Imax) plot of the Pulse Stress I-V PVAc Characteristics
Source: Researchers Fieldwork, 2023

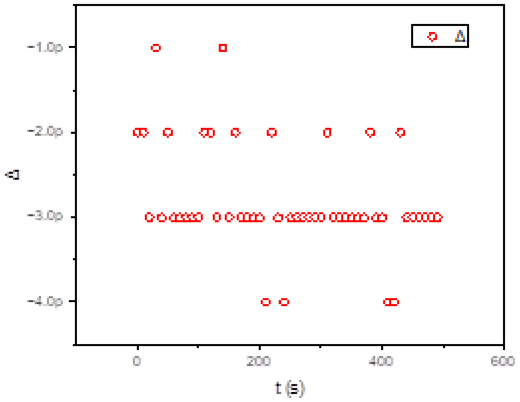

Fig. 27: Shift plot of the Pulse Stress I-V Characteristics Curve
Source: Researchers Fieldwork, 2023

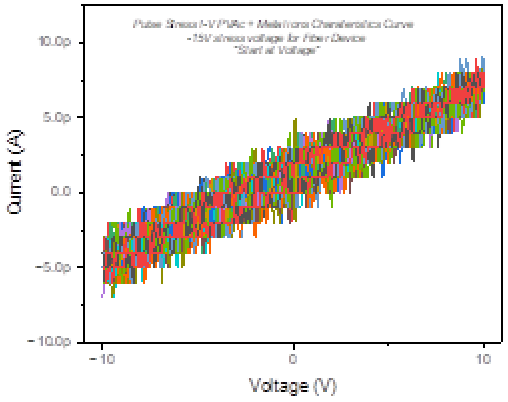

Fig. 28: Pulse Stress I-V PVAc (+ metal ion) Characteristics Curve for Fiber Device of -15V (Start at Voltage)
Source: Researchers Fieldwork, 2023

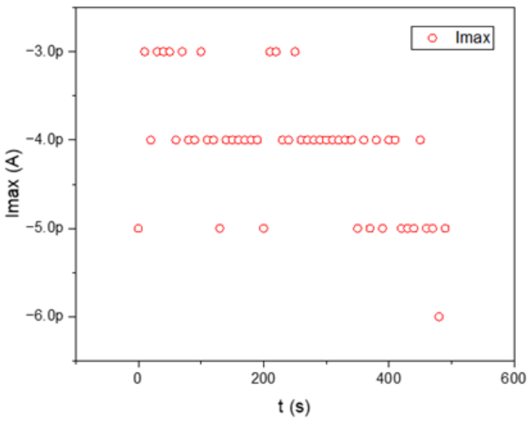

Fig. 29: Maximum current (Imax) plot of the Pulse Stress I-V PVAc Characteristics
Source: Researchers Fieldwork, 2023

The stress test at higher voltage illustrates an increased shift in current response and area plots. These shifts imply the cumulative effect of voltage stress on ionic redistribution, which may increase device functionality and also pose a risk of breakdown in extreme conditions. Greater ionic mobility is suggested by the bigger shifts in Imax at higher voltages, which may improve synaptic mimicry. Significant stress, however, may result in structural deterioration or ion trapping, underscoring a trade-off between dependability and performance. In line with theoretical models, this result indicates that interface stability and ionic saturation are important components of neuromorphic performance. Paul and Paul (2022) highlighted how crucial it is to balance durability and plasticity in polymer-based memory systems by regulating stress voltage. This research adds credence to this by showing that increased stress improves LTP/LTD mimicking but necessitates precise calibration to prevent irreversible harm [11].

4. Conclusion and Recommendation

This research offers important insight into the neuromorphic properties of metal-ion-doped polyvinyl acetate (PVAc) devices. The devices showed great promise in reproducing synaptic plasticity characteristics like long-term depression (LTD) and long-term potentiation (LTP) through thorough I-V characterization and pulse stress testing. The findings showed that during the first stress cycles, the devices show progressive increases in current, simulating the synaptic strengthening seen in biological systems. Although these devices may successfully replicate short-term neuromorphic behaviors, the observed saturation in plasticity points to a crucial limitation: ionic redistribution and material stability may restrict their long-term efficacy. Higher voltage stress tests also showed improved ionic mobility, but they also highlighted the possibility of device breakdown in harsh environments. In conclusion, PVAc (+ metal ions) devices show promise for neuromorphic applications; nevertheless, next research should concentrate on enhancing their performance through multi-ionic system exploration, stress parameter optimization, and durability improvement. These discoveries aid the continuous development of polymer-based memory systems for bio-inspired computing applications. The study recommends improving device stability under varying voltages and environmental conditions should be of priority. To increase consistency and scalability, advanced fabrication methods like layer-by-layer assembly and precision doping should be investigated. Device longevity and operational stability will be improved by encapsulation techniques that protect devices from environmental elements including humidity and temperature changes. Thorough comparisons with alternative neuromorphic materials can also reveal performance deficiencies and guide design enhancements.

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