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FPGA Based Tuneable Memristor For Programmable Analog Circuits

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Abstract**—** Memristor is one of the non-volatile two terminal device which stacks the resistance values in its memory and explore the resistance values as outcome directly proportional to the input voltage variances. The benefit of memristor and its cognitive voltage adjustment impact various digitally tuneable circuits with N-number of intermediate bits. The proposed system focused on deriving analog circuits with memristors. The design of memristor using configurable look up table is developed initially. The proposed memristor is getting varied from 100Ohms to 1000Kohms with the step size of 10ohms where the voltages are varied to represent the resistance from the stacked memory. The low power configurable bits simply tune the performance of the analog circuit such as gain amplifier, threshold comparator, oscillator, Schmitt trigger and filters.

Keywords— Low power, Memristor circuits, Clock generator, Analog circuits, Low latency systems.

I. INTRODUCTION

Memristors play a crucial role in the development of smart systems, particularly in creating memristor-based intelligent memory solutions. Their ability to dynamically tune memory parameters enables cognitive adaptability, making them a key component in advanced computing and artificial intelligence applications. One of the most significant advantages of memristive memory is its ability to enhance the performance of smart devices by providing energy-efficient, high-speed, and non-volatile data storage. This competitive edge makes memristor-based memory an essential element in next-generation computing architectures. Additionally, memristors are instrumental in reservoir-based computation systems, where their unique switching mechanisms facilitate efficient processing of complex and non-linear data. These systems leverage memristive switching to create adaptive, reconfigurable networks capable of handling real-time data processing. The integration of a dynamic tuning mechanism further enhances system efficiency, enabling smart computing frameworks to evolve and respond to changing data patterns. As a result, memristors are revolutionizing the landscape of intelligent computing by offering scalable, high-performance solutions for a wide range of applications, from neuromorphic computing to edge AI systems.

A memristor is a fundamental electronic component that combines memory and resistance, where resistance values are stored in memory and can be reconfigured as needed. This unique capability allows the device to have multiple resistance states, which can be retrieved into the main system whenever required. The concept of memristors is widely applied in circuit design, particularly in scenarios where resistance plays a crucial role in optimizing performance. In analog circuits, such as filters and gain amplifiers, the feedback resistor significantly impacts circuit behavior by influencing gain, stability, and frequency response. This has led to extensive research into the development of advanced memristor-based devices that enhance circuit efficiency and adaptability. One such innovation involves dynamically adjusting resistance values with a step size of 10 kilohertz, which provides precise control over signal processing and circuit functionality. The ability to fine-tune resistance in real-time opens new possibilities for designing adaptive and reconfigurable electronic systems, making memristors a promising technology for future advancements in analog and digital circuit applications.

A memristor is a passive electronic device that fundamentally retains the integral value of the current passing through it, making it a crucial component in modern circuit design. One of its key characteristics is its ability to store and transfer information through changes in resistance, similar to how magnetic flux enables data transfer between devices. The working principle of a memristor is closely related to that of a variable resistor or a trimpot, where resistance values change dynamically in response to applied voltage or current. Unlike traditional resistors, which have fixed values, the memristor's resistance varies based on its past electrical states, allowing it to function as a non-volatile memory element.

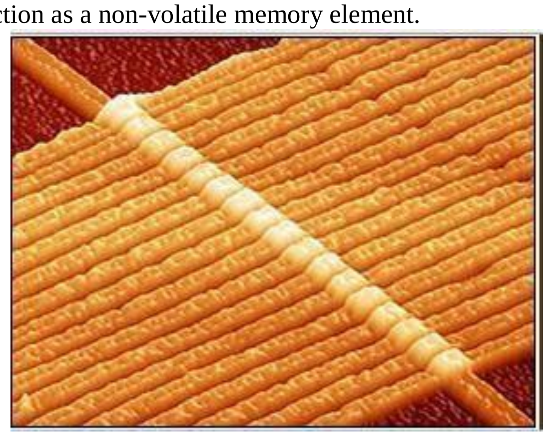

Fig 1. Memristor Structure

Fig 1. illustrates the structure of a memristor, a fundamental electronic component that differs significantly from conventional resistors. Traditional resistors have fixed resistance values, which remain constant under normal operating conditions. These conventional resistors follow a linear, time-invariant model, meaning their resistance does not change with variations in voltage or current. In contrast, memristors exhibit a dynamic resistance behavior, where the resistance value depends on the history of electrical signals applied to them. This property allows memristors to function as non-volatile memory elements, making them highly valuable in advanced computing applications, including neuromorphic systems and adaptive circuits. Their ability to store and adjust resistance over time enables energy-efficient, intelligent memory storage and processing, setting them apart from standard resistors in modern electronic design. This property makes it highly suitable for neuromorphic computing, artificial intelligence, and next-generation memory storage. Additionally, the memristor operates as a time-invariant, nonlinear resistor, enabling more efficient energy storage and computation within electronic circuits. By exploring the fundamental behavior of resistance modulation, memristors pave the way for more adaptive and energy-efficient electronic systems, revolutionizing the fields of memory storage, analog computing, and artificial intelligence hardware.

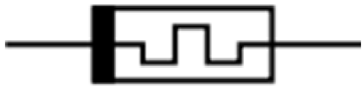

Fig 2. Memristor Symbol

Fig 2. Shows the memristor symbol, This proposed approach introduces a reconfigurable memristor that is developed and emulated using a digitally customized architecture, enabling it to cater to a wide range of circuit applications. By leveraging its reconfigurability, the memristor can dynamically adapt to function as various essential components, including a gain amplifier, Schmitt trigger, comparator, and signal conditioner. This adaptability makes it an integral part of modern circuit design, where flexibility and efficiency are critical. Furthermore, the proposed architecture extends beyond fundamental circuit elements, facilitating the development of more complex configurations such as filters and oscillators. These components can be dynamically reconfigured within the memristor framework, offering enhanced performance and versatility in electronic system design. By integrating such a digitally controlled reconfigurable memristor, the approach paves the way for more intelligent, adaptive, and multifunctional circuits that can optimize performance based on application-specific requirements.

In comparison to traditional architectures that rely on separate components. Latency is also notably reduced due to the high-speed switching characteristics of memristors and their capacity to handle multiple operations with a single reconfigurable unit. Together, these benefits make reconfigurable memristors a promising component for efficient, low-power, and high-speed applications in integrated circuit design.

The rest of the journal is well organized by providing supporting articles study in Section II. System methodology and hardware specifications in section III, followed with design methodology and execution paradigm in Section IV etc. the rest of the journals discuss the navigated results and concluded with future scope.

II. BACKGROUND STUDY

Y. Xu et al. (2021) The author conducted research on wearable electronic devices utilizing edge computing, where the primary system is developed with memristors, most of which are non-volatile. These devices incorporate artificial neurons, enabling advanced computational capabilities. Additionally, large-scale neuromorphic circuits are integrated based on memristor technology, ensuring compatibility with edge computing systems and enhancing overall performance. The drawback of the existing system development is that the limited role of memristor during the fabrication process plays a significant key in making decision [7].

H. Liu et al. (2021) The research framework centers on the development of memristor-enabled chaotic systems, which have garnered significant interest in the creation of innovative products. A memristor functions as a resistor with memory, dynamically adjusting its resistance based on past electrical activity. Beyond memristors, the study explores other programmable passive devices, such as meminductance and memcapacitance, expanding the possibilities for next-generation electronic components. To optimize performance, parametric results are continuously updated, allowing precise tuning of memristor values in response to varying voltage inputs. This adaptability enhances the stability and efficiency of chaotic systems, paving the way for groundbreaking applications in computing and signal processing[8].

S. N. Truong et al. (2020) The author introduced a crossbar architecture utilizing memristors with bipolar inputs, achieving a reduction in power consumption ranging between 16.7% and 7.2%. This optimization is particularly beneficial in identifying defective architectures, where a binarized neural network approach is emphasized. The developed crossbar architecture is specifically designed for image processing applications, with configurations tested on 10 different images, showcasing its efficiency and adaptability in handling complex computational tasks[9].

T. Kahale et al. (2022) The memristor serves as a fundamental design element for developing tunable resistors, capacitors, and inductors. With the growing demand for advanced computing circuits, the simulation of memristive models has become a key area of evaluation. In this study, three distinct memristive models are implemented with flexible integration, enabling the development of high-pass and low-pass filters. The nodal system facilitates the simulation and testing of memristors, ensuring accurate performance assessment. Additionally, the author explores the results through various neuromorphic circuits, providing a comprehensive evaluation of their effectiveness in real-world applications. [10].

S. B et al. (2024) The author introduced a system that leverages silicon wafers to facilitate long-wavelength communication using switching memristor devices. The simulated design incorporates a programmable switching element, enabling room temperature measurement and data storage within configurable memory stacks. Additionally, an illuminance sensing mechanism is developed, integrating memory to capture and process external light variations effectively. The system also simulates the processing time for memristor wavelength adjustments, optimizing performance across multiple switching configurations. This approach enhances both sensing accuracy and memory efficiency, making it a promising solution for advanced communication and environmental monitoring applications [11]. The memristor based synapse design is one of the primary circuit considered for analysis as the existing state of art approach provides various insights, the role of memristor is significant in tuneable analog circuits[12].

III. SYSTEM DESIGN

In the existing system, a detailed study is conducted on the design, implementation, and performance evaluation of memristor-based logic gates, including fundamental types like NOT, AND, NAND, OR, NOR, XOR, and XNOR gates.

Beyond basic gates, combinational logic circuits, such as adders, subtractors, and 2×1 multiplexers, are also developed to showcase the versatility and potential of memristor-based architectures in digital logic. This system emphasizes how memristors, as a key component, can improve the efficiency and integration density of logic circuits.Additionally, the impact of various CMOS technology nodes, specifically 90 nm and 180 nm, on power consumption at the chip level is investigated, providing insights into the scalability and energy efficiency of memristor-based circuits across different fabrication scales. By evaluating the performance of these memristor-based circuits at multiple technology nodes, the study highlights potential trade-offs in power consumption and area requirements, enabling better design decisions for integrating memristors into chip-level logic circuit implementations. The findings from this investigation offer valuable benchmarks for future designs that leverage both the speed and power advantages of memristor technology within different CMOS technology constraints.

IV. METHODOLOGY

A. Circuit of Memristive system

Integrating memristors into existing semiconductor fabrication processes presents significant challenges due to the distinct material and structural requirements of memristive devices compared to traditional CMOS technology. Achieving compatibility often involves modifying or adding steps to standard fabrication flows, which can affect process complexity, yield, and cost. Additionally, ensuring that memristors seamlessly integrate with CMOS circuitry while preserving their unique properties—such as non-volatility, low power requirements, and high switching speed—requires precise control over material deposition, annealing, and patterning processes.

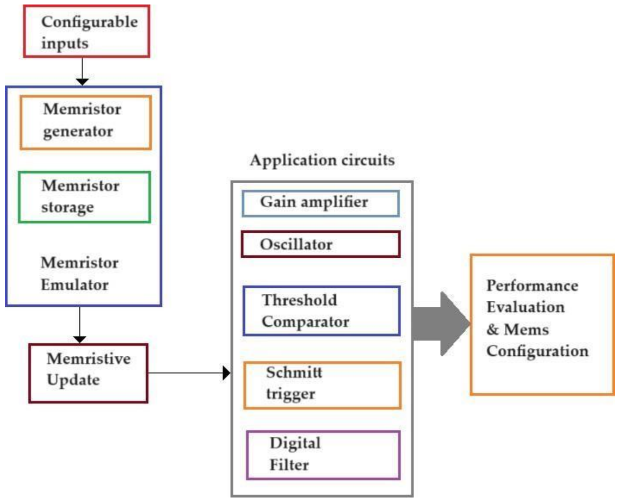

Fig 3. Proposed architecture of programmable devices through memristor

Fig 3. Shows the proposed architecture. Another critical aspect is variability. Memristors often exhibit variability in their switching characteristics, endurance, and retention, which can stem from inconsistencies in material properties, fabrication variations, and environmental factors. This variability can impact the reliability and predictability of memristor-based circuits, especially in high-precision applications. To address these challenges, techniques such as robust circuit design, variability-aware modelling, and adaptive control mechanisms are essential. Ensuring consistent performance in memristor-based circuits may also involve error-correction schemes, redundancy, and calibration methods that can compensate for deviations in individual device behavior. Addressing these fabrication and variability issues is essential for advancing memristor technology from research to commercial viability within integrated circuit applications.

To evaluate the performance of the memristor emulator, multiple application circuits have been implemented, leveraging the emulator's ability to replicate memristive behavior accurately. These circuits include fundamental components like amplifiers, comparators, and filters, as well as more complex arrangements such as oscillators and signal conditioners. Each circuit is tested to assess the functionality, power efficiency, speed, and area consumption of the memristor-based design, providing insight into the practical advantages and limitations of using memristors in real-world applications.

A comparative analysis is also performed between conventional circuit designs and those implemented with memristive components. This comparison allows for a deeper understanding of the distinctions in performance metrics. Memristive circuits typically demonstrate lower power consumption and reduced area requirements due to their compact design and low-power switching characteristics. However, performance metrics such as latency and reliability are carefully scrutinized to understand any trade-offs involved. This side-by-side evaluation highlights the potential of memristors as a replacement for or complement to traditional components, particularly in applications where power efficiency and density are prioritized over conventional speed or stability constraints.

Hardware implementation

Memristor based reconfigurable oscillator is developed.

V. RESULTS AND DISCUSSIONS

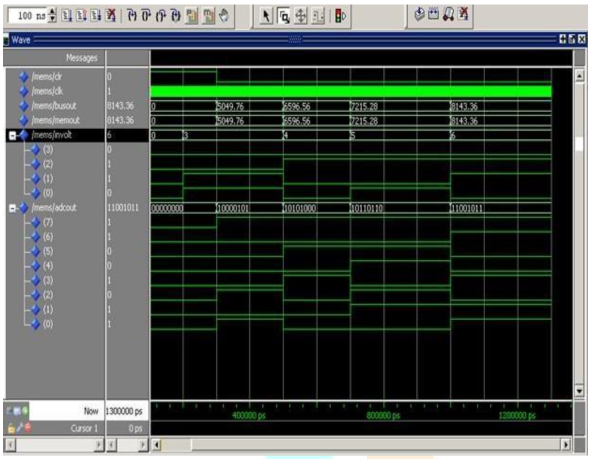

Fig 4. Design of memristor

Fig 4. Shows the programmable Memristor tuning process. The resistance values are getting updated from the base value of 100 HZ at every instant of clock pulse hit the system. The tuning process in automatic mode is shown in the simulation, where the manual configuration of memristor value is getting selected by the low power config bits range from “00000000” to “11111111”.

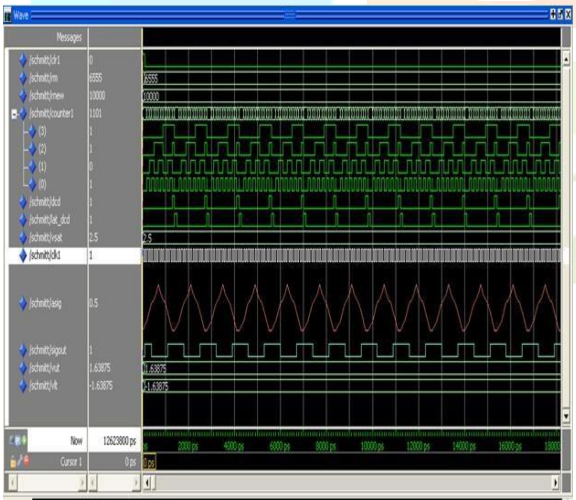

Fig.5. Schmitt trigger development

Figure 5 presents the simulation results of a programmable Schmitt trigger, where a memristor is integrated into the feedback section of the circuit. This configuration enables continuous performance updates, as the circuit dynamically adjusts to changes in the memristor's values at every instant. This adaptive behavior enhances the stability and responsiveness of the Schmitt trigger, making it highly suitable for applications requiring precise signal processing and threshold detection.

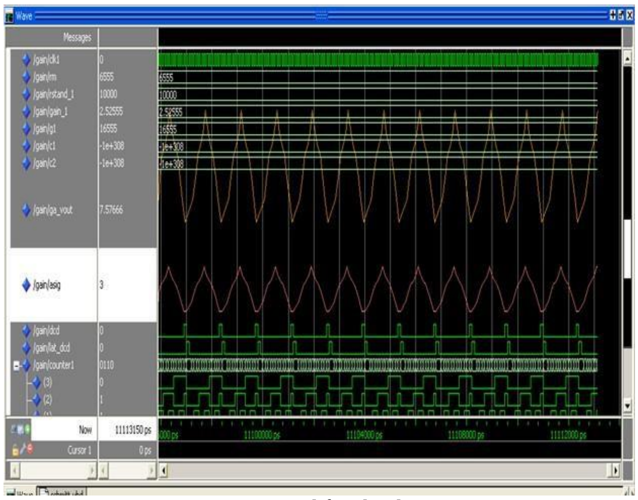

Fig 6. Gain amplifier development

Fig 6. Shows the simulation result of programmable gain amplifier adopted with memristor. The gain of the proposed design is updated with respect to the feedback resistor connected with memristor.

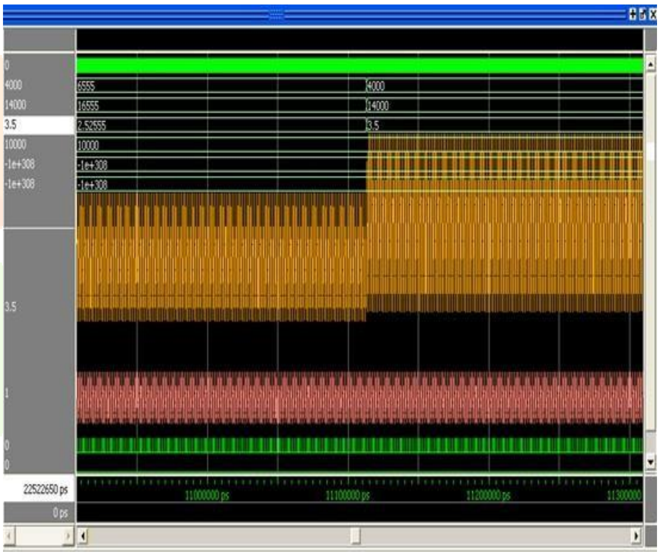

Fig 7 Configurable architecture

Fig 7. Shows the results of reconfigurable architecture developed with switching of memristance values with tunable configuration bits.

Further the presented architecture is developed using reconfigurable field programmable gate arrays (FPGA), where the programmable analog circuits are evaluated in terms pf planning the device utilization, power consumption and latency of the architecture. Probably the XILINX Spartan devices are primary choice to test the working of programmable analog devices using memristor. The testing of the circuit functionality is evaluated through oscilloscopes in digital storage, logical analyzers for detection of glitches etc.

The research work can be further explored by adding up more programmable analog circuits such as oscillators, phase locking loops, filters etc.

Hardware implementation

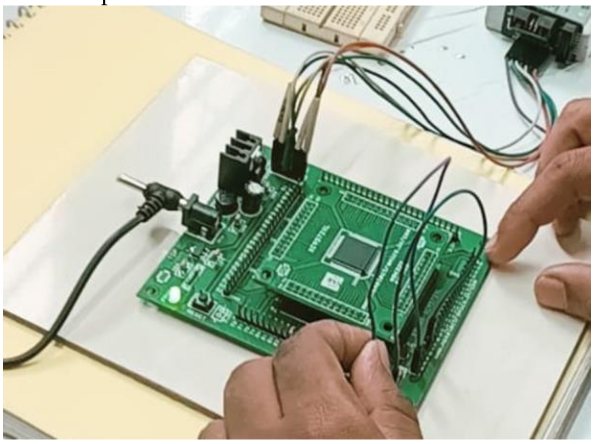

Fig 8. Hardware implementation of Programmable memristor

Fig 8. Shows the FPGA hardware implementation of tunable memristor enabled oscillator circuit is tested with 2^8 combinations of tunable voltage parameter vary the resistance values. The XILINX XC9572XL hardware a low power cool runner device is considered for analysis. The device is operated at +3.3V and 40MHZ clock.

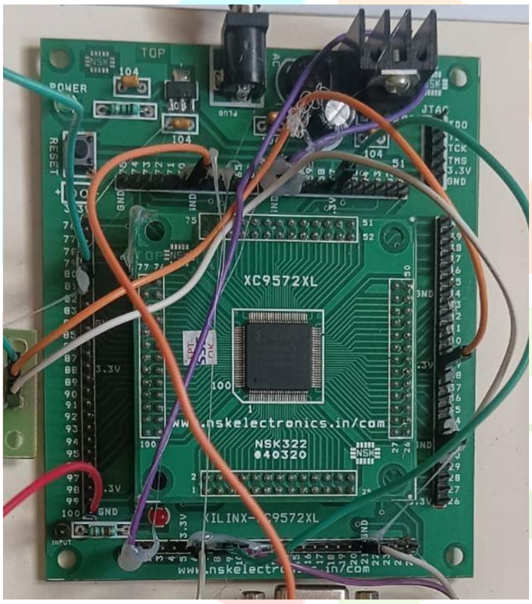

Fig 9. Test and Evaluation of XC9572XL hardware

Fig 9. Shows the test and evaluation of xilinx test hardware implemented with reconfigurable oscillator circuit. The CPLD hardware is tested with tuning the input pints to configure the tunable clock frequency.

VI. CONCLUSION

Memristors, as non-volatile two-terminal devices, store resistance values in memory and dynamically adjust their output in direct proportion to input voltage variations. Their ability to enable cognitive voltage adjustments significantly impacts digitally tunable circuits, accommodating a wide range of intermediate bit configurations. This study focused on developing analog circuits using memristors, beginning with the design of a configurable lookup table. The proposed memristor exhibits a tunable resistance range from 100Ω to 1000kΩ, with a step size of 10Ω, allowing precise voltage-controlled resistance adjustments. The integration of low-power configurable bits enhances the performance of various analog circuits, including gain amplifiers, threshold comparators, oscillators, Schmitt triggers, and filters. These findings highlight the potential of memristor-based designs in advancing energy-efficient and highly adaptable electronic systems..

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