

Fully Digital Write-in Scheme for Multi-Bit Memristive Storage

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Abstract—Memristors have been used in various applications, including single- and multi-bit storage units. The non-linear voltage-current relation in memristors is often seen as a problem, necessitating complex circuits and methods for a reliable write-in. In this paper, we take advantage of this phenomenon for storing more than one bit of information in a single memristor using digital bit streams. First, we demonstrate how two bits of information can be stored and read back from a single memristor unit. Then, we propose encoding schemes that can enhance the reliability of digitally writing two and three bits of data in a single memristor. To verify the reliability of this method for multi-bit data storage, we have run simulations based on the most prominent simulation models available.

I. INTRODUCTION

Electrical engineers are quite familiar with circuits which include the three basic passive circuit elements - resistor, capacitor and inductor. However, for the first time, in 1971 Leon Chua proposed a fourth circuit element, describing the relation between charge (q) and flux (ϕ) [1]. The resistance of the so called Memristor device, depends on the total charge passed through the device [1], [2]. The device characteristics of the memristor open the floor for many new fields of application [3]–[7]. One of the most important applications is, as expected, using it as a memory element. For example, [8]–[10] and others have invested considerable effort in studying the design of memristor based memory units. The main advantage of using memristors is given by the fact that in a modern chip, the number of transistors required to store data (e.g. in an SRAM) has a significant -and increasing- impact on the total transistor count [11]. In consequence, implementation of new memory architectures by using memristors would decrease the total amount of device leakage current dramatically [9].

Since HP developed the first passive memristor in 2008 [12], there have been works on single-bit [8]–[10], [13] and multi-bit [14], [15] memory storages. The unique $\phi - q$ characteristic of memristors however, leads to a nonlinear $v - i$ characteristic which makes it difficult to determine the pulse size for achieving a certain state [14], [15]. Therefore, it has been seen as a problem for multilevel memory designs [14], [15]. To overcome this problem, researchers have developed methods, some fairly complicated, which use analog circuits and op-amps for both reading and writing [14], [15]. Using op-amps and analog circuits for read-out seems to be inevitable

[8], [14], [15]. However, as we will present, the aforementioned characteristic can be taken advantage of, to store more than one bit in memristors, using circuits which are compatible with digital designs. These circuits are hence less complex. Although digital bit streams have been used for setting synaptic values [16], the exact stored value and recovery of the stored value are not of high importance in such applications. In memory applications, on the other hand, this is of paramount importance. Therefore, in this paper we discuss the reliability of the storage and read-out, as well as how encoding can help improving these parameters.

The rest of this paper is organized as the following: In the next section, we briefly review the aforementioned unique characteristics of memristor and show how it can be taken advantage of, in order to store more than one bit in each memristor. In Section III, we present the digital writing method for storing two bits of data on a single memristor, as well as the read-out circuit. Then, in Section IV, we show the results of our simulations which confirm the feasibility of the proposed approach. In Section V, we improve the reliability of the storage, and the number of stored bits, using different proposed encoding schemes. Finally, we conclude the paper in Section VI, which entails our plan for future works as well.

II. THEOREM

It is a well established phenomenon in the literature, that the resistance of a memristor depends on the charge flown through it [1], [17]. This can be modeled in various ways, one of the most prominent of which is [17]:

$$R(q(t)) = R_{\text{off}} + \frac{R_{\text{on}} - R_{\text{off}}}{e^{-4k_m(q(t)+q_0)} + 1}. \quad (1)$$

where R_{off} and R_{on} are the maximum and minimum resistance of the memristor, $q(t)$ is the charge flown through the memristor with the initial value of q_0 . Finally, k_m is a constant which represents physical characteristics of the device such as doping of the semiconductor and its size.

According to (1), not only the resistance, but also changes of the resistance in a memristor due to identical voltage pulses depend on its current state [14], [18]. This characteristic seen as a hardship [14], [15] can be turned into an opportunity based on the following theorem.

Theorem: *Distinct output resistances correspond to distinct input patterns, which allows storage of more than one bit in a single memristor.*

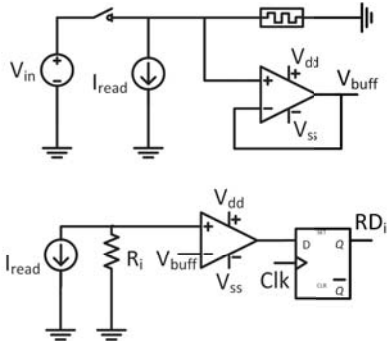


Fig. 2. For reading out, V_{buff} is fed to three comparators connected to D Flip-flops which provide RD_i bits (for simplicity, only one set is depicted).

current pulse (here a rectangular pulse with the magnitude of $1\mu\text{A}$ and width of 1ms), the resulting voltage across the memristor is buffered and fed to three comparator circuits (only one of which is shown at the bottom of Fig. 2, for simplicity). The voltage across the memristor is then compared with the voltage produced by applying a similar current pulse to predetermined resistance values. If the voltage across the memristor is greater than the voltage read from the memristor, the comparator will flip to high output and a “1” will be stored in the respective flip-flop output (RD_i). This implies that the resistance of the cell is below the respective resistor, R_i .

We note that the read-out current pulse is chosen to be significantly smaller than input pulses, so that it would have a smaller effect on the state of the memristor. Nevertheless, however small this effect is, it needs to be compensated for. Therefore, similar to [8], [15], by applying another controlled pulse in the reverse direction, this effect can be compensated for. The advantage of using current pulses, compared to the voltage pulses used in [8], [15], is that the effect of positive and negative current pulses on the resistance change will be similar whereas as proved in Section II, it is not the case for voltage pulses. That is, a negative voltage pulse, due to inherent characteristics of the memristor and its non-linear voltage-current relationship, cannot precisely compensate a positive voltage pulse and will leave residual extra charges (positive or negative). Therefore, state of memristor needs to be checked and more often refreshed to compensate the residual charges as well.

Using current sources, as proposed here, the complex method of read-out effect elimination is reduced to an automatic compensation through a reverse current pulse, which is considerably simpler than the one used in [14]. Automatic refreshing may lead to extra power consumption, however, it eliminates the state-read operation or counting process for the refreshing proposed in [15]. Therefore, it is going to be simpler. We note that this technique may not prove efficient for all types of memristor technologies (e.g. for non- TiO_2 memristors), or scenarios (e.g. for power constrained applications). Therefore, in order to compensate for the destructive effect of uncompensated read-outs (for power critical applications or where this technique is not efficient), other scenarios, as discussed in [15], can be employed to compensate for the read-out effect.

IV. SIMULATIONS

In order to evaluate the practicality of the proposed approach in storing data in memristors, we have simulated the proposed circuit in LTspice. We have used the most prominent model (namely, Biolek’s [17]) of TiO_2 memristors, described by (1). The following values were used for the model parameters (as given by the authors [17]); $R_{on} = 100\Omega$, $R_{off} = 10k\Omega$, $k_m = 10000$, and $R_{init} = 5k\Omega$. Input signals last 10ms and 1ms, respectively for input voltages and read-out current pulses. The amplitudes are $\pm 0.5\text{V}$ for “1” and “0” input pulses and $-1\mu\text{A}$ for read-out current pulses. The value of R_i resistors used in this set of simulations are 5170, 5130, and 5010Ω for $i=1,2$, and 3 respectively.

Comparators and their precision play a crucial role in practical implementation of the read-out circuit, which determine to what level the small differences between states can be distinguished. To account for their non-idealities, we have used the model for an off-the-shelf op-amp, namely LT1012 (with $25\mu\text{V}$ maximum offset). This ascertains that the assumed values for parameters such as offset, are realistic and accounted for, i.e., this circuit can -in practice also- perform as expected.

Fig. 3 shows the result of simulation for a sample case, namely “01” input. In this figure, the blue curve shows the voltage across the memristor (namely V_{in}) and the black curve shows the RD_1 output. For simplicity, RD_2 and RD_3 which as expected remained zero during the whole simulation are not shown. As we can see, shortly after applying the read-out current at 3.1 secs (zoomed-in area) the output of RD_1 turns to “1”.

This and other simulations for all outputs satisfied the expected outputs as shown in Table I, where the expected outputs represent “ RD_3 & RD_2 & RD_1 ” combination. Once these values are obtained, different inputs are distinguished properly and with simple logic circuits these outputs can be turned into binary values once again. This proof of concept confirms the feasibility of digital streaming approach for storing, and successfully retrieving two bits of information on a single memristor.

V. ENCODING AND THREE-BIT STORAGE

In this section, we present the impact of the range of the memristor and the encoding of data on the reliability of the read-out.

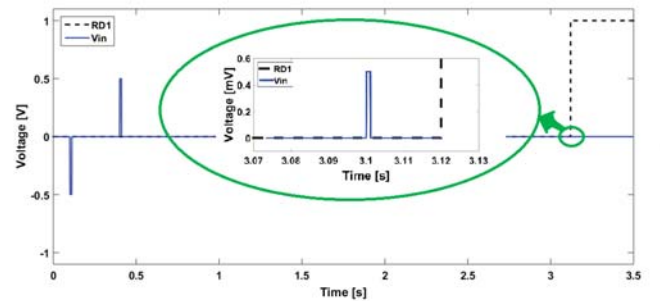


Fig. 3. Simulation results for “01” input. Shortly after applying the read-out current at 3.1s (zoomed in), the output of RD_1 flips to “1” representing the stored data. RD_0 and RD_2 remained zero and are not shown for simplicity.

A. Exploration of the Memristance Range

Trying to store three bits or more in a single memristor can have a negative impact on the reliability of the read-out, due to smaller differences between resistances at different states. Expanding the range of the memristor (between R_{on} and R_{off}), helps in reducing the relative sensitivity. Although, the relative difference in memristance between inputs with the same number of ones or zeros can be thus improved, this improvement is not necessarily proportional to the expansion of the range.

For example, in a memristor with a range of 100Ω - $10k\Omega$, if the difference between “10” and “01” is 10Ω , in a memristor with a range of $1k\Omega$ - $100k\Omega$, the difference -according to our simulations- can be 17Ω . This is validated in our simulations, where two memristors are considered: memristor 1 (M_1) with the range of 0.1 - $10k\Omega$ and memristor 2 (M_2) with the range of 0.5 - $100k\Omega$. The pulse width is set to $100ms$, and the amplitudes are set to $\pm 0.5V$ for “1” and “0” inputs. Initial state of memristor is assumed to be $5k\Omega$. Table II presents the memristance value for different 3-bit data patterns.

TABLE II. RESISTANCE FOR MEMRISTORS WITH DIFFERENT RANGES OF MEMRISTANCE. M_1 : 0.1 - $10k\Omega$ AND M_2 : 0.5 - $100k\Omega$.

| Input | R_{M_1} (k Ω) | R_{M_2} (k Ω) |
|-------|-------------------------|-------------------------|
| “000” | 7.2453 | 47.2428 |
| “001” | 5.8991 | 28.9629 |
| “010” | 5.8997 | 28.9710 |
| “011” | 3.9089 | 5.0033 |
| “100” | 5.8990 | 28.9600 |
| “101” | 3.9078 | 4.9898 |
| “110” | 3.9088 | 5.0014 |
| “111” | 1.0396 | 0.5000 |

For instance, the memristance difference between “011” and “101” is 1Ω for M_1 , whereas it is 14Ω for M_2 . This indicates that inputs with the same number of ones or zeros can be differentiated easier in the memristor with a wider resistance range.

Although in this way the difference is increased, it is yet small and requires complex complementary circuits, such as the one used in [14], to set the values precisely. It also needs precise comparators, such as the one assumed in [15], to read the values out. To alleviate the problem of close resistance at different states, and in order to improve reliability without using analog write-in circuits or extra circuits with extensive complexity for the read-out operation, we propose two encoding schemes. These techniques lead to a significantly higher relative memristance difference between inputs with the same number of ones and zeros. As the number of memristors are not increased with encoding, the area of the memory remains constant, except for the addition of an encoder for the whole system (which is a memory block with hundreds to thousands of memory cells). Therefore, the area used for the encoder is considerably negligible.

B. Uniform Input Encoding

In the first scheme, we employ a simple encoding method. In this technique, we append the most significant bit (MSB) to the end of the input, as shown in Fig. 4. In other words, input “100” is encoded as “1001”. The simulation setup is the

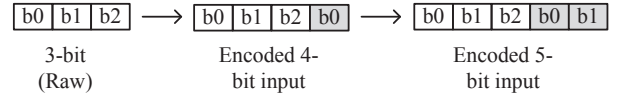


Fig. 4. Uniform Input Encoding of 3-bit input data to 4-bit and 5-bit data.

same as stated values earlier in Section IV, with memristor M_1 chosen for simulation, and initial memristance set to $5k\Omega$. Table III and IV show the effect of encoding for 2-bit input and 3-bit input data, respectively.

Table III presents the memristance for raw input data and encoded data. Originally, the memristance difference between “01” and “10” is nearly 1Ω , whereas when encoded to 3-bits, the relative memristance is nearly $1.9k\Omega$. As such, larger implementation errors (such as inaccuracy of reference values) and variations (of fabrication, implementation or between different cells) can be tolerated. In [15], a potential of up to 6% physical variation in fabrication process is observed and in [14], 10% memristance variation is assumed. However, given that the minimum distance between the memristance states after the proposed encoding is 19% (whereas it was 0.2% before), a flawless operation despite those variations is expected.

TABLE III. MEMRISTANCE FOR 2-BIT INPUT WITH UNIFORM ENCODING.

| Input | Raw (k Ω) | Encoded value (k Ω) | Encoding Scheme |
|-------|-------------------|-----------------------------|-----------------|
| “00” | 6.6384 | 7.2453 | “000” |
| “01” | 5.0005 | 5.8998 | “010” |
| “10” | 4.99955 | 3.9079 | “101” |
| “11” | 2.5919 | 1.0396 | “111” |

Similarly, the effect of encoding on 3-bit data is presented in Table IV. Here, we show the memristance when the 3-bit data is encoded to 4-bit, and 5-bit (N.B., in this case first *two* MSB bits are appended to the end of the data). From Table IV, we can see that the memristance difference between the two inputs of “001” and “100” for the raw (3-bit), encoded to 4-bit and encoded to 5-bit data, is respectively 0.1Ω , $1.64k\Omega$ and $1.4k\Omega$. However, if we notice, the relative memristance difference between “001”, and “010” when encoded to 4-bit, is $<1\Omega$. This is because the appended bits for both are the same. This difference is larger between these two inputs in the case of 5-bit encoded data. Simply because the appended bits in this case are not the same anymore. Nonetheless, in some instances the values are still significantly close to each other which endangers a reliable retrieval of the stored data. Hence, further improvements as it follows are necessary.

C. Non-Uniform Encoding

To address the problem of close values and similar appended bits in the uniform encoding scenario, we propose another encoding scheme, shown in Table V. In this scenario, appendices were selected not based on the two MSBs, but rather such that the distance between all states is maximized. To this end, some bits are appended with two bits, some with one, and some with none.

As we see in Table V, using the new encoding scheme the minimum difference between all inputs is increased to 905.6Ω ,

TABLE IV. MEMRISTANCE FOR 3-BIT INPUT WITH TWO DIFFERENT UNIFORM ENCODING SCHEMES.

| Input | Raw (k Ω) | Encoded to 4-bit (k Ω) | Encoding Scheme | Encoded to 5-bit (k Ω) | Encoding Scheme |
|-------|-------------------|--------------------------------|-----------------|--------------------------------|-----------------|
| "000" | 7.2453 | 7.7431 | "0000" | 8.1511 | "00000" |
| "001" | 5.8991 | 6.6384 | "0010" | 7.2451 | "00100" |
| "010" | 5.8997 | 6.6389 | "0100" | 5.9002 | "01001" |
| "011" | 3.9089 | 5.0004 | "0110" | 3.9095 | "01101" |
| "100" | 5.8990 | 4.9996 | "1001" | 5.8968 | "10010" |
| "101" | 3.9078 | 2.5906 | "1011" | 3.9073 | "10110" |
| "110" | 3.9088 | 2.5919 | "1101" | 1.0404 | "11011" |
| "111" | 1.0396 | 0.1000 | "1111" | 0.1000 | "11111" |

whereas it was previously only 0.5 Ω in the 4-bit encoding scheme and 2.2 Ω in the 5-bit encoding scheme shown in Table IV. This minimum distance being always larger than 11%, shows that potential physical and fabrication variations mentioned in [14], [15] can be tolerated by the system. Hence, using this non-uniform encoding scheme, three bits of data can be digitally streamed to a single memristor and the stored values can be reliably recovered using the read-out circuit presented in Section III.

VI. CONCLUSION

In this paper after a brief introduction we discussed the specific theory which allows us to use the non-linear behavior of memristors to our advantage for storing more than one bit of data in memristors via a simple bit streaming process. This process is compatible with digital circuits and in contrast to existing methods does not require analog or mixed-signal circuits and scenarios previously used for write-in process. Next, we presented the details of writing and reading-out methods which can be implemented using compact circuits with low complexity and requirement. The proposed method has smaller complexity compared to other works in the literature, and a smaller footprint and most importantly, it uses only digital circuits for writing in values in a memristor.

Further, we simulated the proposed methods successfully, thus demonstrating the feasibility of the proposed approach. The most crucial part of a practical implementation is the precision and real-world constraints of the op-amp used in the read-out circuit. Hence, to ascertain the feasibility of our approach, models of an off-the-shelf available op-amp, namely LT1012, were used in the simulations which take into account the non-idealities such as the off-set.

We then proposed two encoding techniques, with which the distance of values stored in the memristor is increased in order

TABLE V. MEMRISTANCE FOR 3-BIT INPUT WITH NON UNIFORM ENCODING, WHERE "-" PRESENTS NO INPUT APPLICATION.

| Input | Raw (k Ω) | Encoded Value (k Ω) | Encoding Scheme |
|-------|-------------------|-----------------------------|-----------------|
| "000" | 7.2453 | 8.1511 | "00000" |
| "001" | 5.8991 | 5.8991 | "001--" |
| "010" | 5.8997 | 7.2455 | "01000" |
| "011" | 3.9089 | 3.9089 | "011--" |
| "100" | 5.8990 | 4.9996 | "1001--" |
| "101" | 3.9078 | 2.5906 | "1011--" |
| "110" | 3.9088 | 1.0404 | "11011" |
| "111" | 1.0396 | 0.1000 | "1111--" |

to ascertain a more reliable storage and retrieval of two- and three-bit values in a single memristor, despite the potential implementation inaccuracies and cell to cell variations. This technique being compatible with digital circuits, does not require any additional complex analog or mixed-signal circuits, which are currently used in the literature to increase the reliability of the storage and retrieval.

A. Future Works

We hope that in future we can expand this method by further evaluating the related issues for the memory system, and simulating the feasibility of faster storage and retrieval of data as well as larger number of bits in a single memristor. Moreover, by obtaining a memristor, we plan to implement the proposed circuit and verify the proposed approaches in practice as well.

Last but not least, we will explore applications of memristors in domains such as learning and approximate computing. In such applications, not only retrieving the exact value of stored data is not necessary, but often it burdens the system with extra computational loads. We believe, in such applications, by storing more data in memristors in a simple digital-compatible fashion such as proposed, and an approximate retrieval of data, learning systems can benefit from a smaller memory footprint and perform faster, with virtually no loss of performance.

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