# Electronically Controllable Fully Floating Memcapacitor Circuit

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## Abstract

Memcapacitor is a type of capacitor but exhibits nonlinear behavior, and its capacitance depends on the past capacitance value. Researchers focused on the memcapacitors and meminductors upon postulation of memristor which is the forth passive fundamental circuit element. Memcapacitor emulator circuits have continuously been designed by researchers since it cannot be found as discrete circuit elements. A number of memcapacitor emulators have been offered in the literature to investigate its usability in CMOS designs. However, the offered designs have some insufficiencies such as grounded restriction, being composed of complex structure, etc. In this study, we

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designed a simple multioutput operational transconductance amplifier (MO-OTA)-based fully floating and electronically controllable memcapacitor emulator circuit. The circuit is composed of only two MO-OTAs, two analog multipliers, two grounded passive elements, and four transistors. This proposed circuit can also be implemented in VLSI and on breadboard using discrete circuit elements. Performance analyses were completed via using TSMC 0.18 µm parameters. Finally, the obtained results of the proposed fully floating emulator circuit are consistent with the expected memcapacitors behavior. This makes the circuit suitable for ideal memcapacitor emulator.

**Keywords** Memcapacitor · Memristor · Emulator · Floating design · MO-OTA · Decremental configuration · Incremental configuration

## 1 Introduction

In spite of the postulation of memristor as a new fundamental circuit element by Chua [5] in 1971, researchers did not focus on this new element until its physical implementation in 2008 [30]. In the literature, it is possible to find many studies on the memristor, which is predicted to reduce the physical size and power consumption of memory in all electronic devices such as computers. Several application areas have been suggested for memristive devices, such as oscillator design [6, 12], neural networks applications [17, 33], design and analysis of memory circuits [10, 11, 13, 25], chaotic circuits and systems [20, 31, 37], logic circuit elements design [16, 26, 34], filter design [1], signal processing [18], controller design, and several analog circuit applications [21–24]. Different structures of memristor emulator circuits have been proposed for use in most of these studies and future studies of researchers [9, 14, 29, 38–40].

On the other hand, Chua et al. stated that there should be capacitors and inductors with memory, called memcapacitors and meminductors, similar to memristors, in 2009 [8]. Although there are studies on the realization of solid-state and ionic memcapacitors in the literature [15, 19], new studies on emulator circuits and modeling of memcapacitors continue to be made since it is not yet available as a two-terminal device. Biolek et al. [3] designed and implemented two charge-controlled behavioral memcapacitor models, the first of which takes into account the memcapacitor state description and the second of which uses the memcapacitor's constitutive relationship as the only input data, and whose capacitance is controlled by the amount of electric charge carried through it. Biolek et al. [4] proposed a synthesis of mutators that convert emulated memristor to memcapacitor and meminductor and presented the simulation results with an example of the circuit configuration. Wang et al. [36] presented a memcapacitor simulator based on a light dependent resistor (LDR) memristor. The proposed memcapacitor model is based on the analog model of a memristor, and the success of the proposed structure is given along with the simulation and experimental results. Babacan [2] presented a simple operational transconductance amplifier (OTA)-based memcapacitor and meminductor emulator circuit that does not contain any memristor circuits or models. It is also stated that the simulation results of the proposed simple emulator circuit are compatible with the characteristic behaviors of the memcapacitor

and meminductor. In conclusion, compared to floating structures, a lot of research [2, 4, 7, 32, 35, 36, 41] is grounded, which limits the scope of their application.

Pershin and Ventra [27] proposed second generation current conveyor (CCII) and memristor-based floating memcapacitor. It consists of four CCIs, one floating memristor, and two passive elements. The work by Zheng [43] reported that AD844-based floating memcapacitor is proposed. It contains four AD844s, two resistors, two capacitors, and single varactor diode. Yu et al. [42] presented floating memcapacitor including four AD844s, single TL084, nine passive elements. Sharma et al. [28] proposed CCII and multiplier-based floating memcapacitor. It is composed of two CCIIs, single analog multiplier, and three passive elements. These mentioned floating memcapacitors circuits [27, 28, 42, 43] both contain floating passive elements and cannot be adjusted electronically. Moreover, it contains many active and passive elements.

In this study, different from current reporting's, MO-OTA-based fully floating memcapacitor emulator circuit is presented. The circuit is composed of only two MO-OTAs, two analog multipliers, four transistors which behave as voltage-controlled capacitor, and two grounded passive circuit elements. Simulation results for the proposed circuit are given with all details by using LTSpice simulation program. As a result, the obtained results are suitable for defined memcapacitor behavior in the literature.

## 2 Memcapacitor Emulator Circuit

The proposed memristor is designed using two MO-OTAs as active circuit elements. The used MO-OTA has two positive and one negative current outputs. The circuit symbol and used internal structure are shown in Fig. 1a, b, respectively.

The presented memcapacitor emulator circuit is shown in Fig. 2 The circuit is composed of two MO-OTAs, four transistors which are used to obtain voltage-controlled capacitor, one grounded resistor, and one grounded capacitor. The used NMOS transistors which behave voltage-controlled capacitor are driven by the multiplication of the voltages on resistor and capacitor. The multiplication, i.e., ($V_F = V_{(C)} \times V_{(R)}$), also drives the second MO-OTA and provides the appropriate current which flows through the memcapacitor. All the bulk terminals of the four NMOS transistors which are used as capacitor are connected to the ground. The circuit structure is fully symmetric as input voltage could have been applied to any terminal of the circuit. If the voltage of X terminal becomes higher than Y terminal of the circuit, decremental memcapacitor can be obtained. The circuit behaves incremental memcapacitor when X terminal voltage is lower than Y terminal of the circuit.

## 3 Simulation Results

Memcapacitor is a type of capacitor so it should be observed that there is a phase shift between the applied current and voltage. The input signal is applied to the decremental terminal of the memcapacitor emulator circuit. The voltage and current of the proposed memcapacitor are shown in Fig. 3a. Also, the voltage and charge of the memcapacitor
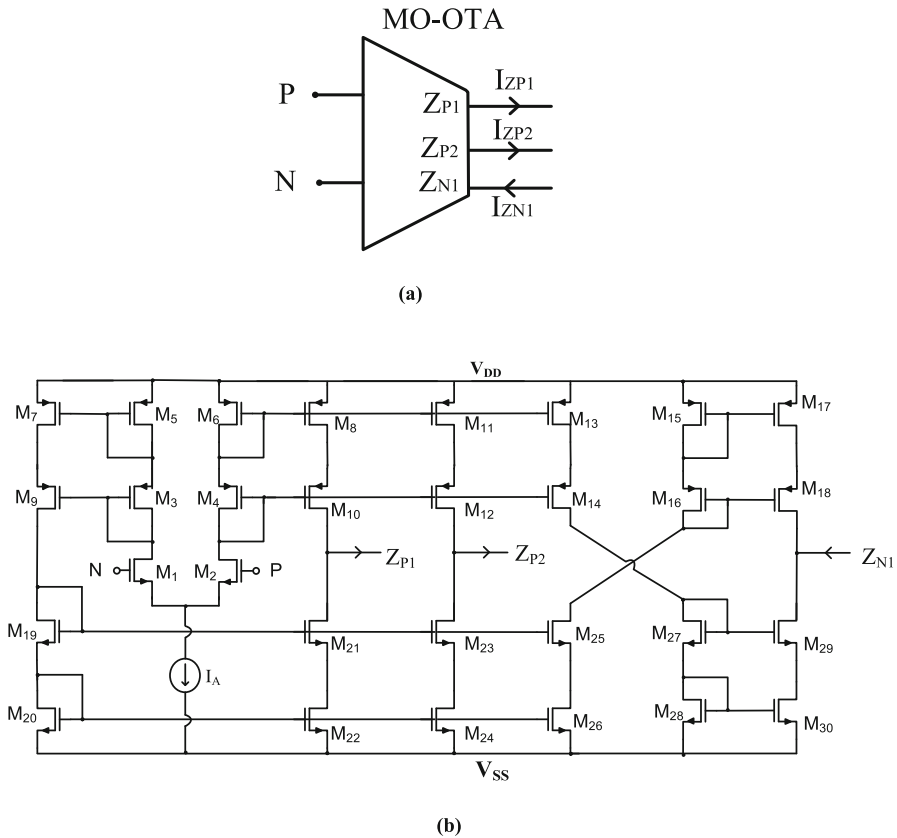
**Fig. 1 a** Circuit symbol of MO-OTA and **b** its internal structure. Here, $I_A = 30\ \mu A$, $(W/L)_{1-2,19-30} = 20\ \mu m/0.7\ \mu m$, $(W/L)_{3-18} = 40\ \mu m/0.7\ \mu m$ $V_{DD} = -V_{SS} = 0.9\ V$

should become the same phase so the applied voltage and obtained charge are given in Fig. 3b to show the performance of the proposed circuit.

Pinched hysteresis loop is a well-known key property of mem elements when sinusoidal input signal is applied. Voltage/current relationship of memristor, current/flux relationship of meminductor, and voltage/charge relationship of memcapacitor exhibit pinched hysteresis loops. We applied sinusoidal input voltage to the circuit, and pinched hysteresis loop was obtained as shown in Fig. 4.

One of the common properties of memelements is their frequency-dependent characteristic. Memory elements should exhibit a dependence on the applied frequency, such as capacitors, inductors, and memristors. The pinched hysteresis loops of the proposed circuit are depicted in Fig. 5 when sinusoidal signals with three different frequencies are applied. Additionally, there is no distortion observed as the applied frequencies increase, and the pinched hysteresis curves remain unchanged when different frequencies are applied.
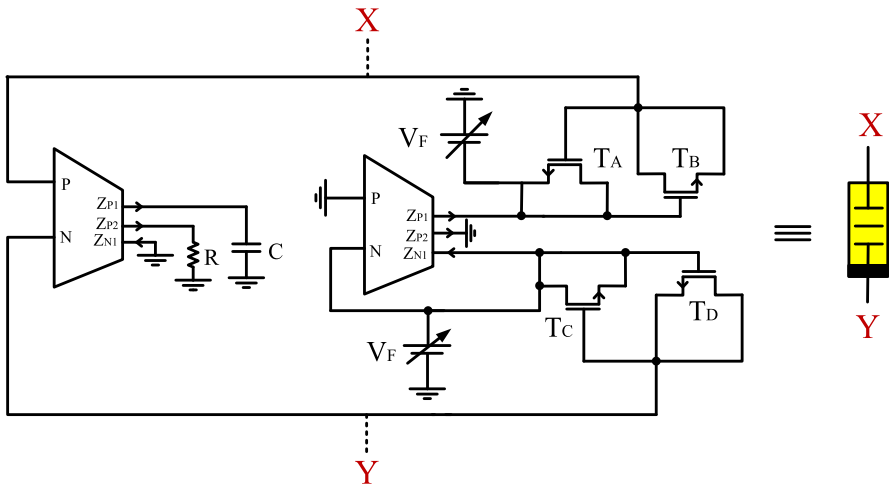
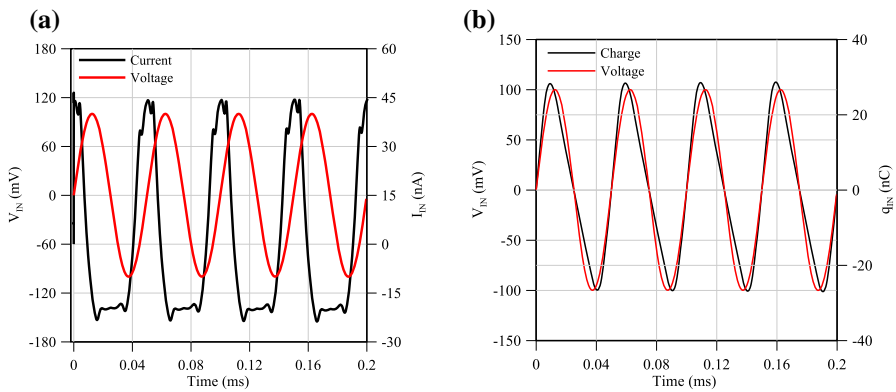**Fig. 2** Proposed MO-OTA-based memcapacitor emulator circuit



**Fig. 3 a** Voltage/current and **b** voltage/charge performance of the memcapacitor circuit

Memcapacitor is a type of memory element and stores information even when no signal is applied. Also, memcapacitors are sensitive to both signal directions and signal amplitude. To investigate this performance of the circuit to the signal amplitude and direction, we applied three positive signals to the X and Y terminals of the memcapacitor emulator, respectively. As shown in Fig. 6, charge is decreasing and increasing during the first and second three pulses which are applied to the X terminal and Y terminal of the memcapacitor, respectively.

Also, there is no charge change between voltage pulses so it can be pointed out that memcapacitor emulator has nonvolatile behavior.

The behavior of the emulator circuit can be controlled by using different resistor and capacitors. The charge changes depending on different resistor and capacitor values are shown in Fig. 7 More resistor and capacitor values provide more charge flow in

**Fig. 4** Charge–voltage relationship of memcapacitor emulator. Here, the applied signal is sinusoidal 100 mV with 20 kHz frequency
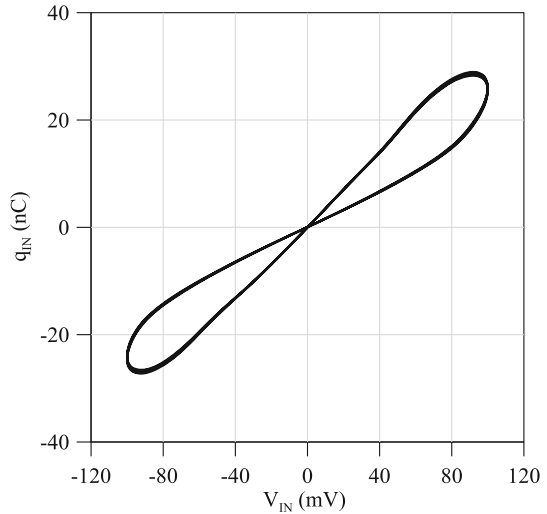
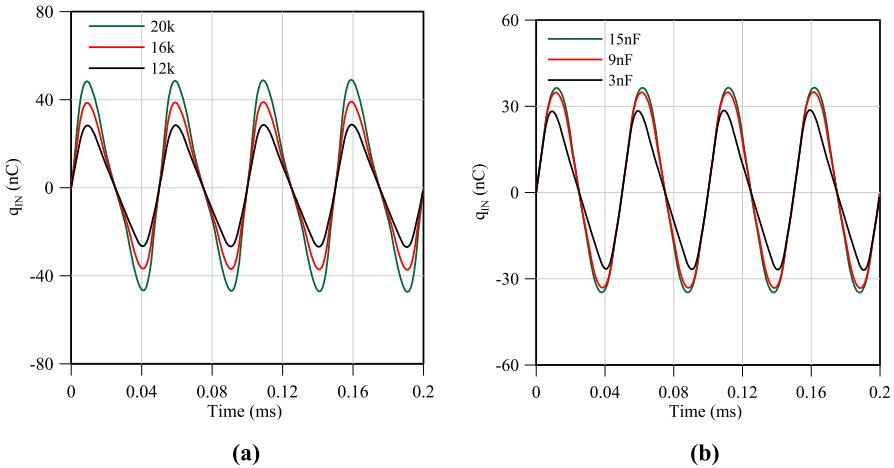**Fig. 5** Charge–voltage relationship of memcapacitor emulator with different frequency ranges
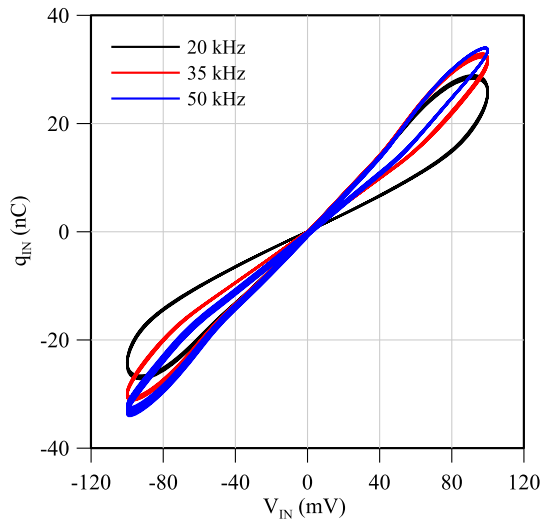
the circuit. If resistor or capacitor is controlled electronically, it can be specified that memcapacitor emulator circuit is electronically controllable.

Out of the control with resistor and capacitor, memcapacitor circuit behavior can be controlled using MO-OTA bias current. The bias current directly affects the charge/voltage relationship of memcapacitor emulator circuit. As expected, the charge increases and decreases with increasing and decreasing bias current of MO-OTA, respectively. Figure 8 depicts charge/voltage relationship when bias currents are selected as 20 μA, 30 μA, and 40 μA values.

Transistors are used as grounded capacitors. $T_A$, $T_B$ and $T_C$, $T_D$ transistors act grounded parallel capacitors. The capacitor values can be controlled by changing the
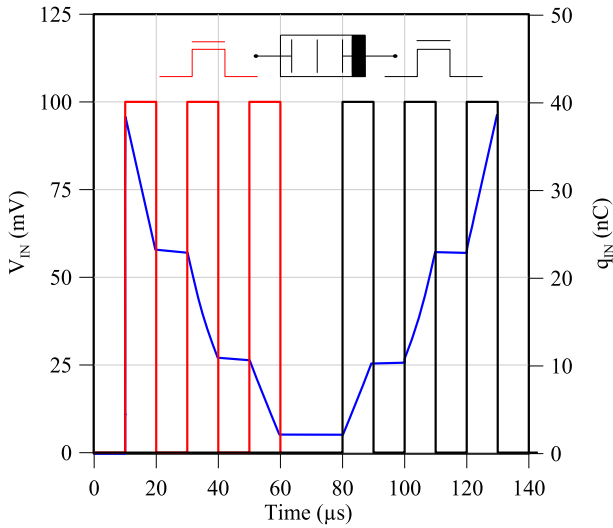
**Fig. 6** Variations in the memcapacitance for each pulses. Red and black lines represent voltage pulses which are applied to the decremental and incremental terminal of memcapacitor, respectively. Also, blue line represents charge response (Color figure online)



**Fig. 7** Variation in charge when **a** different resistor and **b** capacitor values are used

W/L ratios of these transistors. As shown in Fig. 9, the charge/voltage relationships of the proposed circuit depending on different W/L ratios are investigated. As expected, more charge values can be obtained using high W/L transistor ratios.

We investigated the charge/voltage relationship of the proposed circuit with different temperatures. As shown in Fig. 10, the charge/voltage relationship of the circuit exhibits stable behavior at a wide range of the temperature.

**Fig. 8** Charge/voltage relationship of the circuit depends on various MO-OTAs bias currents
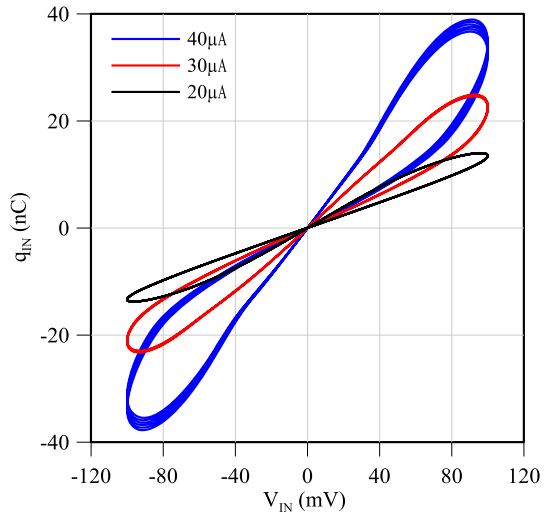


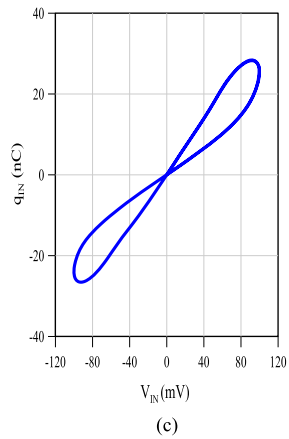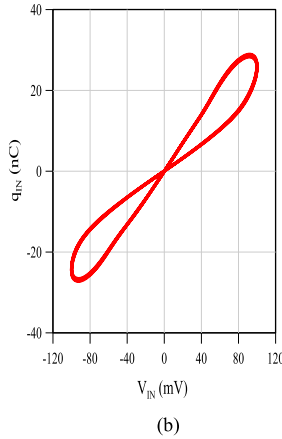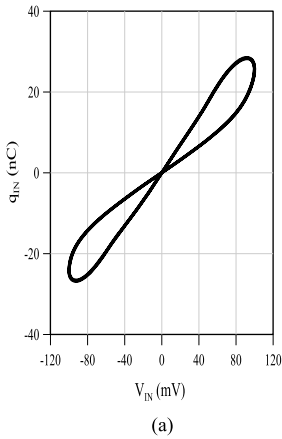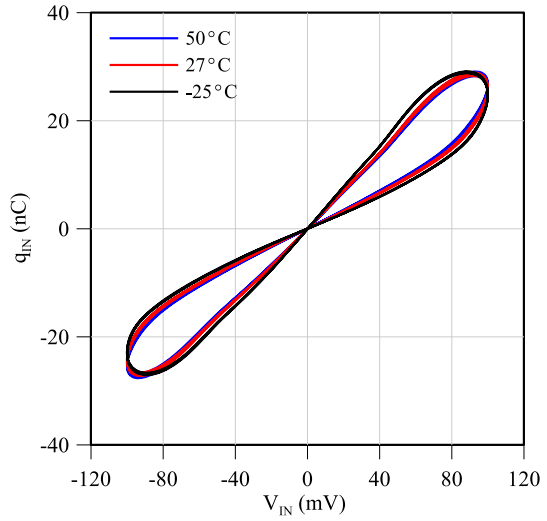**Fig. 9** Charge–voltage relationship of memcapacitor emulator when different W/L values are used
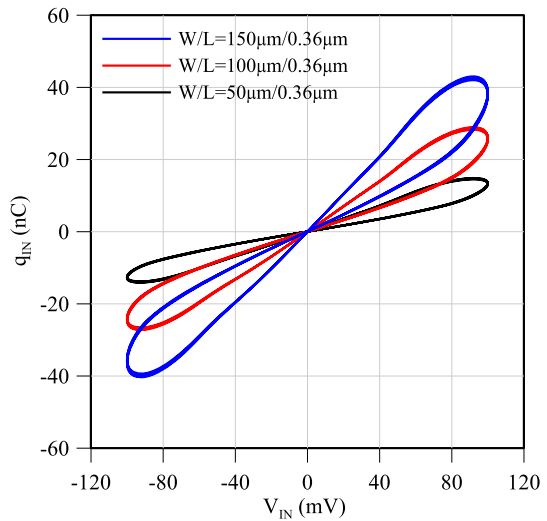


Finally, the circuit can be operated at different frequencies by changing capacitor value. The capacitor value directly affects the operation frequency of the circuit. As shown in Fig. 11, similar hysteresis loops are obtained at various frequencies for different capacitor values.

We compared our circuit with previous studies in term of used circuit element counts, circuit structure, whether a mutator is required or not, and electronically controllable property. As shown in Table 1, any floating elements are not used, and a mutator is not required to implement memcapacitor. Also, the proposed circuit is both floating and electronically controllable. In conclusion, the designed memcapacitor circuit consists of all good and required properties in a single structure.

**Fig. 10** Charge–voltage relationship of memcapacitor emulator with different temperatures





(a)

(b)

(c)

**Fig. 11** Charge–voltage relationship of memcapacitor emulator for different capacitor and frequency values **a** $C = 3\text{nF}, f = 20$ kHz **b** $C = 6\text{nF}, f = 10$ kHz **c** $C = 12\text{nF}, f = 5$ kHz

**Table 1** Comparison of our circuit with previous studies

| Ref | Active component # | Passive component # | Floating element | Grounded floating | Frequency (Hz) | Requirement of mutator | Electronically controllable |
|---|---|---|---|---|---|---|---|
| [41][a] | 3 AE | 4 | Yes | Grounded | 500 Hz | No | No |
| [41][b] | 3 AE | 3 | Yes | Grounded | 500 Hz | No | Yes |
| [35] | 1 AE | 3 | No | Grounded | 500 kHz | No | No |
| [7] | 2 AE, 1 Tr | 3 | No | Grounded | 1 kHz | No | Yes |
| [32] | 1 AE, 1 M | 1 | No | Grounded | 100 kHz | Yes | Yes |
| [27] | 4 AE, 1 M | 2 | Yes | Floating | NA | Yes | No |
| [43] | 4 AE | 5 | Yes | Floating | 160 kHz | No | No |
| [42] | 5 AE | 9 | Yes | Floating | 4 kHz | No | No |
| [28] | 2 AE, 1 M | 3 | Yes | Floating | 16 kHz | No | No |
| This study | 2 AE, 4 Tr | 2 | No | Floating | 20 kHz | No | Yes |

*AE* active element, *Tr* transistor, *M* memristor
[a]Fig. 2 in[41]
[b]Fig. 3 in[41]

## 4 Conclusion

This paper presents MO-OTA-based electronically controllable fully floating memcapacitor emulator circuit design. This circuit has a very simple structure and is suitable for both VLSI implementation and building on breadboard using discrete circuit elements. Also, both terminals of this proposed circuit can be connected to any places of the circuit thanks to its fully floating structure. The transistors are used as voltage-controlled capacitor and derived from MO-OTAs. Many analyses for the proposed circuit are given in this paper to demonstrate the high performance of circuit using TSMC $0.18\,\mu\text{m}$ parameters. Finally, all results for the proposed fully floating emulator circuit are compatible with the expected memcapacitor behavior.

### Declarations

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