An energy-efficient multistage charge pump for MEMS microphone

Rongshan Wei^{a)} and Jue Wang

College of Physics and Information Engineering, Fuzhou University,
Fuzhou, Fujian, 350116, China

a) wrs08@fzu.edu.cn

Abstract: This paper proposes an energy-efficient, 12-stage charge pump with constant threshold voltage. This new charge pump utilizes 2 pairs of non-overlapping clocks. Under control of an extra pair of clocks, each charge pump cell (CPC) is equivalent to a switch. Without reduction by a threshold voltage and the limitation of body effects, a higher output voltage than that of the traditional charge pump is obtained by the proposed circuit, which is fabricated in a 0.18 μm complementary metal-oxide semiconductor (CMOS) process. With an input voltage from 0.7 V to 1.4 V, the output voltage range is from 5.8 V to 12.5 V. With a 2-pF load capacitor, the power consumption is only 62.7 μW at maximum DC output voltage of 12.5 V. This circuit is intended to generate an on-chip bias voltage for a microelectromechanical systems (MEMS) microphone.

Keywords: charge pump, MEMS microphone, body effect, threshold voltage

Classification: Electron devices, circuits and modules

References

- [1] A. Cheng: *Design of a Readout Scheme for a MEMS Microphone* (Master of Science, Delft University of Technology, Delft, 2009).
- [2] J. Weigold, *et al.*: “A MEMS condenser microphone for consumer applications,” *MEMS* (2006) 86 (DOI: [10.1109/MEMSYS.2006.1627742](https://doi.org/10.1109/MEMSYS.2006.1627742)).
- [3] S.-S. Je, *et al.*: “A directional capacitive MEMS microphone using nano-electrodeposits,” *MEMS* (2009) 96 (DOI: [10.1109/MEMSYS.2009.4805328](https://doi.org/10.1109/MEMSYS.2009.4805328)).
- [4] P. Malcovati, *et al.*: in *Nyquist AD Converters, Sensor Interfaces, and Robustness*, ed. P. Malcovati (Springer, New York, 2013) 149–174.
- [5] J. Citakovic, *et al.*: “A compact CMOS MEMS microphone with 66 dB SNR,” *ISSCC Dig. Tech. Papers* (2009) 350 (DOI: [10.1109/ISSCC.2009.4977452](https://doi.org/10.1109/ISSCC.2009.4977452)).
- [6] J. F. Dickson: “On-chip high-voltage generation in MNOS integrated circuits using an improved voltage multiplier technique,” *IEEE J. Solid-State Circuits* **11** (1976) 374 (DOI: [10.1109/JSSC.1976.1050739](https://doi.org/10.1109/JSSC.1976.1050739)).
- [7] J. T. Wu, *et al.*: “1.2 V CMOS switched-capacitor circuits,” *ISSCC Dig. Tech. Papers* (1996) 388 (DOI: [10.1109/ISSCC.1996.488729](https://doi.org/10.1109/ISSCC.1996.488729)).
- [8] J. T. Wu and K. L. Chang: “MOS charge pumps for low-voltage operation,” *IEEE J. Solid-State Circuits* **33** (1998) 592 (DOI: [10.1109/4.663564](https://doi.org/10.1109/4.663564)).
- [9] J. Shin, *et al.*: “A new charge pump without degradation in threshold voltage due to body effect,” *IEEE J. Solid-State Circuits* **35** (2000) 1227 (DOI: [10.1109/4.891111](https://doi.org/10.1109/4.891111)).

- 1109/4.859515).
- [10] D. S. Hong and M. N. El-Gamal: “Low operating voltage and short settling time CMOS charge pump for MEMS applications,” *ISCAS* (2003) 281 (DOI: [10.1109/ISCAS.2003.1206254](https://doi.org/10.1109/ISCAS.2003.1206254)).
- [11] A. H. Alameh, *et al.*: “A reconfigurable charge pump in 0.13 μm CMOS for agile MEMS actuation,” *ICECS* (2014) 670 (DOI: [10.1109/ICECS.2014.7050074](https://doi.org/10.1109/ICECS.2014.7050074)).
- [12] B. Razavi: *Design of Analog CMOS Integrated Circuits* (McGraw-Hill, New York, 2001) 706.

1 Introduction

A microelectromechanical systems (MEMS) microphone is an acoustic-to-electric transducer or sensor that converts an acoustic signal to an electrical signal. MEMS microphones are used in many applications, such as telephones, hearing aids, mobile phones, and personal audio systems [1]. An MEMS microphone, whose simplified structure is shown in Fig. 1a [2, 3], consists of 2 conductive plates. The bottom plate is fixed and immovable, while the top plate can vibrate with sound pressure, producing a capacitance variation. An acoustic signal is transformed into a capacitance variation.

The interface circuit for an MEMS microphone, whose block diagram is shown in Fig. 1b [4], typically consists of some sort of preamplifier followed by an analog-to-digital converter (ADC). A charge pump is usually required to generate the microphone bias voltage V_B .

Fig. 1. (a) The basic structure of an MEMS capacitor; (b) The typical block diagram of interface circuits for an MEMS microphone.

To isolate an MEMS capacitor, a very large resistor R_b (on the order of giga-ohms) is connected between the microphone and charge pump [1]. If R_b is infinite, the charge on an MEMS capacitor can be regarded as constant. Based on a constant-charge assumption, the output voltage V_{out} can be expressed as

$$V_{out} = \frac{\Delta C \cdot V_B}{(C_{mic} + C_p - \Delta C)}, \quad (1)$$

where ΔC is the capacitance variation of the MEMS microphone, V_B is the bias voltage, C_{mic} is the capacitance of the MEMS capacitor, and C_p is the parasitic capacitance of the preamplifier and MEMS capacitor. Hence, the capacitance variation is transformed into an electrical signal.

As shown in eq. 1, the amplitude of V_{out} depends on V_B . Therefore, to increase the microphone sensitivity, the value of V_B must be high, typically ranging from 8 V to 12 V [5]. Consequently, a charge pump is usually required to generate the desired value of V_B .

In this paper, the supply voltage V_{DD} is 1.8 V. Some of the main parameters of the charge pump are shown in Table I.

Table I. Parameters of charge pump

Parameter (Symbol)	Value	Note
Input voltage (V_{in})	0.7~1.4 V	Limited by the supply voltage
Output voltage (V_{out})	8~12 V	i) To improve the amplitude of the output voltage ii) Considering the withstand voltage of MEMS
Power consumption	<100 μ W	To reduce power consumption

Section II will introduce the working principle of the Dickson charge pump, analyze its defects in detail, and briefly list some attempts to correct them. Sections III and IV will explain the principles of operation and the measurement results, respectively, of the fabricated charge pump. Finally, conclusions will be discussed in section V.

2 Analysis of existing charge pump topologies

In 1976, Dickson invented charge pump circuits [6], as shown in Fig. 2. Since diode-connected MOS transistors are employed, the charges can be pushed only in 1 direction. The pair of pumping clocks Φ_1 and Φ_{II} are non-overlapping and have an input voltage amplitude of V_{in} . The clocks push the charge voltage upward through the transistors. Considering the impact of parasitic capacitance and the current loading, the voltage fluctuation at each pumping node ΔV can be expressed as

$$\Delta V = V_{in} \frac{C}{C + C_p} - \frac{I_o}{f \cdot (C + C_p)}, \quad (2)$$

where C is the capacitance of the coupling capacitor, C_p is the parasitic capacitance associated with each pumping node, f is the frequency of the pumping clocks, and I_o is the output current loading.

When Φ_1 goes high and Φ_{II} goes low, the voltage at node 1 settles to $V_1 + \Delta V$, and the voltage at node 2 settles to V_2 , where V_1 and V_2 are the steady-state lower voltages at nodes 1 and 2. Both MD₁ and MD₃ are reverse-biased, and the charges are being pushed from node 1 to node 2 through MD₂.

Fig. 2. Dickson charge pump circuits.

The necessary condition for the Dickson charge pump to function is that ΔV is larger than the threshold voltage of transistor V_{th} , which can be expressed as

$$\Delta V > V_{th}. \quad (3)$$

The voltage pumping gain for the second pumping stage G_{V2} is defined as the voltage difference between nodes 1 and 2, which can be expressed as

$$G_{V2} = V_2 - V_1 = \Delta V - V_{th2}, \quad (4)$$

where V_{th2} is the threshold voltage of MD₂, modified by the body effect. If ΔV is not much larger than V_{th} , the body effect cannot be neglected, especially at the high-voltage nodes. In fact, the circuit's output voltage reaches its maximum when the body effect causes the threshold voltage to be equal to ΔV . Therefore, the final output voltage is limited by the body effect, and the voltage pumping gain per stage, G_V , is reduced by V_{th} .

In conclusion, the traditional Dickson charge pump circuit has 2 serious defects:

- 1) The voltage pumping gain per stage, G_V , is reduced by the threshold voltage V_{th} .
- 2) The final output voltage V_{out} is limited by the body effect.

To repair defect 1, Jieh-Tsorng Wu proposed a charge pump using static charge transfer switches (CTSs) in 1996 [7]. As shown in Fig. 3, MS₁–MS₄ are the CTSs. By using the already established high voltage to control the CTS of the previous stage, the upper voltage of the input is equal to the lower voltage, and defect 1 is repaired. However, when MD is reverse-biased, there is a large reverse leakage current, since the CTS's are always connecting.

To remove the reverse leakage current, Jieh-Tsorng Wu proposed another charge pump using dynamic CTSs in 1998 [8]. To repair defect 2, Jongshin Shin [9] and David S. Hong [10] proposed a charge pump with a dynamic body bias voltage in 2000 and 2003, respectively. By using auxiliary transistors to set the body bias voltage, the circuit maintains a constant threshold voltage, but defect 1 still exists. Abdul Hafiz Alameh proposed a reconfigurable voltage doubler [11], which improves drive capability and has a controllable output voltage, but needs a relatively larger chip area and consumes more power. None of the above attempts can repair both defects at the same time.

Fig. 3. Charge pump using static CTSs.

3 Proposed charge pump circuits

Fig. 4 is the block diagram of an energy-efficient charge pump. The pair of clocks, clk and clk_n , control each charge pump cell (CPC) and have a voltage amplitude equal to the supply voltage V_{DD} . The other pair of clocks, clk_{lvl} and clk_{lvl_n} , control each coupling capacitor and have a voltage amplitude equal to the input voltage V_{in} . The main circuit consists of 12 CPCs and a special output stage. Every CPC can be seen as a switch, and clk and clk_n causes them to be connected alternately.

Fig. 4. Block diagram of an energy-efficient charge pump.

Fig. 5 shows the specific circuit of a CPC. MD is the charge transfer MOSFET. When clk goes low and $clk.n$ goes high, the gate voltage of MD drops, since the voltage drop across the capacitor cannot change suddenly, and MD connects. The charge is pushed from node 1 to node 2 through MD, and MD gets into deep liner region. The voltage of node 2 can be expressed as

$$V_2 \approx V_1 + \Delta V, \quad (5)$$

where V_1 and V_2 are defined as the steady-state lower voltages at nodes 1 and 2, respectively. The charge on capacitor C_2 is pushed to capacitor C_1 through transistor M_2 and M_3 . Then, the voltage of node A V_4 can be expressed as

$$V_A = V_2 - |V_{th3}|, \quad (6)$$

where V_{th3} is the threshold voltage of M_3 .

When clk goes high and $clk.n$ goes low, V_A rises by V_{DD} while V_2 rises by ΔV . The voltage difference between the source and gate of MD V_{SG} can be expressed as

Fig. 5. Specific circuit of the CPC.

$$V_{SG} = V_2 - V_A = (V_2 + \Delta V) - (V_2 - |V_{th3}| + V_{DD}) = \Delta V - V_{DD} + |V_{th3}|. \quad (7)$$

V_{DD} is higher than V_{in} , and V_{in} is higher than ΔV , which can be expressed as

$$V_{DD} > V_{in} > \Delta V. \quad (8)$$

Ignoring the difference of the threshold voltage among transistors, V_{SG} is lower than the absolute value of MD's threshold voltage V_{thd} . It can be expressed as

$$V_{SG} < |V_{thd}|. \quad (9)$$

Since the MD cannot conduct and has no reverse leakage charge, the energy-efficient charge pump eliminates defect 1.

As shown in Fig. 5, the CPC employs positive channel metal-oxide semiconductor (PMOS) only and the transistors shares substrate. The voltage of the substrate, N-well, is equal to V_2 . Employing PMOS only can avoid latch-up. Since the source and substrate of MD are connected, the body effect on MD can be removed. This circuit also has the advantage that the charge can flow through drain-sub parasitic PN junction and reduce the setup time.

The output stage is shown in Fig. 4. The proposed circuit employs 2 anti-parallel diodes as the large resistor R_b . The I-V characteristic of the diode shows that charge pump circuits charge the MEMS capacitor rapidly when the voltage drop across the diode is large; while the voltage drop is low, the anti-parallel diodes can be equivalent to a larger resistor [12]. The anti-parallel diodes isolates the MEMS capacitor well at steady-state. In addition, there is a filter consisting of the equivalent resistor and MEMS capacitor. The charge accumulated on the MEMS microphone do not change by much because of the large RC time constant. It reduces the ripple at the output voltage. Furthermore, the output stage saves chip area and reduces the setup time.

This paper proposes an energy-efficient charge pump for an MEMS microphone. By employing an extra pair of clocks to make MD work as a switch, the proposed circuit repairs defect 1. Furthermore, by sharing N-well and connecting to the output voltage of the CPC, the proposed circuit repairs defect 2. In addition, the output stage employs anti-parallel diodes, which can act as an equivalent resistor

and reject the ripple of output voltage. The proposed circuit can cascade with many stages because there is no degradation in the threshold voltage due to body effects, and it generates higher output voltage.

4 Measurement results

The proposed circuit is fabricated in a 0.18 μm CMOS process; the block diagram of the overall test circuit is shown in Fig. 6. The bandgap voltage circuit produces a reference voltage V_{bg} , and the external circuit provides the input signal for a digital-to-analog converter (DAC) through an inter-integrated circuit (I²C). The DAC generates an input voltage V_{in} from 0.7 V to 1.4 V. Fig. 7 shows a photograph of the energy-efficient charge pump; the chip area is 0.35 mm $\times$ 0.125 mm.

Fig. 6. Block diagram of overall test circuit.

Fig. 7. Photograph of the energy-efficient charge pump.

Fig. 8 shows the measurement result of the proposed circuit. With V_{in} ranging from 0.7 V to 1.4 V, the output voltage ranges from 5.8 V to 12.5 V. The output voltage has approximately 196 μV of ripple, peak-to-peak, whereas the maximum power consumption is only 62.7 μW with a 2-pF load capacitor.

The operating clock is set at 2.4 MHz. The lower the working clock frequency, the longer the setup time, and the higher the working clock frequency, the greater the power consumption. As shown in Fig. 8(b), the setup time is 289 μs (10% to 90%), which meets the application scenarios. Without the discharge circuit, the setup time is much shorter at a second time and the power consumption can be reduced.

Fig. 8. (a) Measured output voltage with different input voltages; (b) measured output voltage versus setup time.

Table II summarizes the performance of the charge pump compared to those reported in other papers. As shown in Table II, the proposed circuit has a lower power consumption, lower ripple, and smaller chip area. The output voltage is roughly equal those reported in other papers. Ultimately, the proposed circuit is more suitable for an MEMS microphone.

Table II. Charge pump performance summary and comparison.

Parameter (unit)	This work	[8]	[9]
CMOS technology (μm)	0.18	0.18	0.13
Input Voltage (V)	1.4	1.2	1.2
Clock Frequency (MHz)	2.4	75	50
Number of Stages	12	16	8
Max Output Voltage (V)	12.5	14.8	10.62
Ripple Voltage (mV)	0.196	150	48
Rise Time (μs)	289	65	1.56
Power Consumption (μW)	62.7	759	220
Area ($\text{mm} \times \text{mm}$)	0.35×0.125	0.8×0.9	0.215×0.3

5 Conclusions

The charge pump used for the MEMS microphone requires a high output voltage and low power consumption. This paper proposed a new charge pump that repairs the 2 main defects of traditional charge pump circuits. The proposed circuit is fabricated in a 0.18 μm CMOS process. As seen in the results, the output voltage ranges from 5.8 V to 12.5 V with a 0.7 V-to-1.4 V input and a 2-pF load capacitor, and the power consumption is only 62.7 μW . Compared to charge pump proposed in other papers, this charge pump has advantages in power consumption, ripple voltage, and chip area, and better suits the MEMS microphone.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (No. 61404030).