A New Charge Pump Without Degradation in Threshold Voltage Due to Body Effect

Jongshin Shin, In-Young Chung, Young June Park, and Hong Shick Min

***Abstract*—A new charge-pump circuit with the controllable body voltage is proposed. By adjusting the body voltage, the back bias effect is removed and the threshold voltage of the MOSFET used as a switch is kept constant. With no threshold voltage increase, higher output voltage than the conventional charge pump can be obtained in the proposed charge pump. With two auxiliary MOSFET's used to update the body voltage, the proposed charge pump shows compatible performance of the ideal diode charge pump.**

***Index Terms*—Auxiliary MOSFET, body effect, charge pump, threshold voltage.**

I. INTRODUCTION

THE BODY terminal of MOSFET is generally fixed to a constant voltage to guarantee a stable operation of the device. In the bulk MOSFET, the body is hardly used as an active terminal because of the large body capacitance inherited from well or substrate capacitance. For specific applications, however, more efficient circuit operation can be achieved if the body is used as an active terminal [1]. In this work, a new operation of the charge-pump circuit based on the controlled body voltage will be proposed.

The charge-pump circuit which is used to generate higher voltage than the available supply voltage has wide applications such as the flash memory or EEPROM. Because the demand for high voltage comes from physical mechanism such as the oxide tunneling, the required pumped voltage cannot be scaled as the power-supply voltage is scaled. Therefore, an efficient charge-pump circuit which can achieve high voltage from the available low supply voltage is essential.

In Fig. 1(a), a diode charge-pump circuit that uses the diode as the charge transfer device is shown. The output voltage of a diode charge pump is

$$V_{\text{out}} = (V_{DD} - V_t) \times N + V_{DD} \tag{1}$$

where V_t is voltage drop in the diode and N is the number of stages. The term $V_{DD} - V_t$ may be called the voltage gain per unit stage and its output voltage linearly increases as the number of stage increases. Because forming independent diodes in the same substrate is very unwieldy and the voltage drop across the diode is not scalable, the conventional charge pump proposed by Dickson [2] uses the diode-connected MOSFET as the charge transfer device in place of the diode.

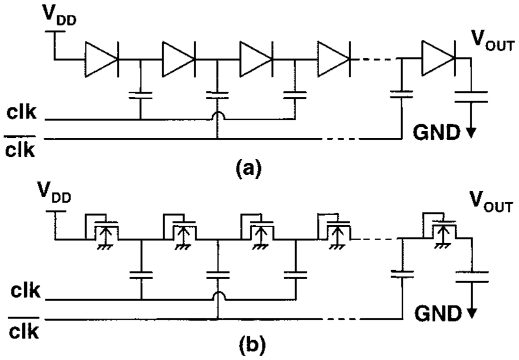

Fig. 1. (a) Diode and (b) Dickson charge pump.

In the Dickson charge-pump circuit as shown in Fig. 1(b), as the voltage of each stage increases by the charge pumping, the threshold voltage of the diode-connected MOSFET increases due to the body effect. The voltage gain $V_{DD} - V_t$ decreases and the output voltage becomes lower than the value obtained by the diode charge pump. Therefore, the output voltage of the Dickson charge pump cannot be a linear function of the number of stages and its efficiency decreases as the number of stage increases. Since the threshold voltage cannot be scaled as much as the scaling trend of the supply voltage, the impact of threshold voltage increase to the output voltage lowering becomes more appreciable in the low supply voltage.

Several attempts have been made to alleviate the V_{th} loss problem [3]–[5]. But they must use complex timing scheme [3] or backward control [4] which may have a risk of reverse current even with auxiliary MOSFET's. Use of floating devices to eliminate the body effects [5] have also been reported. But the resulting charge pump may generate substrate current by floating devices.

In this work, a new charge-pump circuit is proposed where the body of the MOSFET is used as an active terminal to avoid the problem associated with the threshold voltage increase in the charge transfer device. It will be shown from the experimental study that much higher pumping voltage than the value from the Dickson charge pump can be achieved by controlling the body voltage. In Section II and III, respectively, the operation principle and the measurement result of the fabricated charge pump will be explained and the conclusion will be made in Section IV.

II. OPERATION PRINCIPLE OF THE PROPOSED CHARGE PUMP

In Fig. 2, the proposed charge pump is shown by the schematic and the cross-section view. Two auxiliary MOSFET's are introduced to control the body bias as shown in the figure. The source-side auxiliary MOSFET shares the source and the gate with the charge-transfer MOSFET and the drain-side

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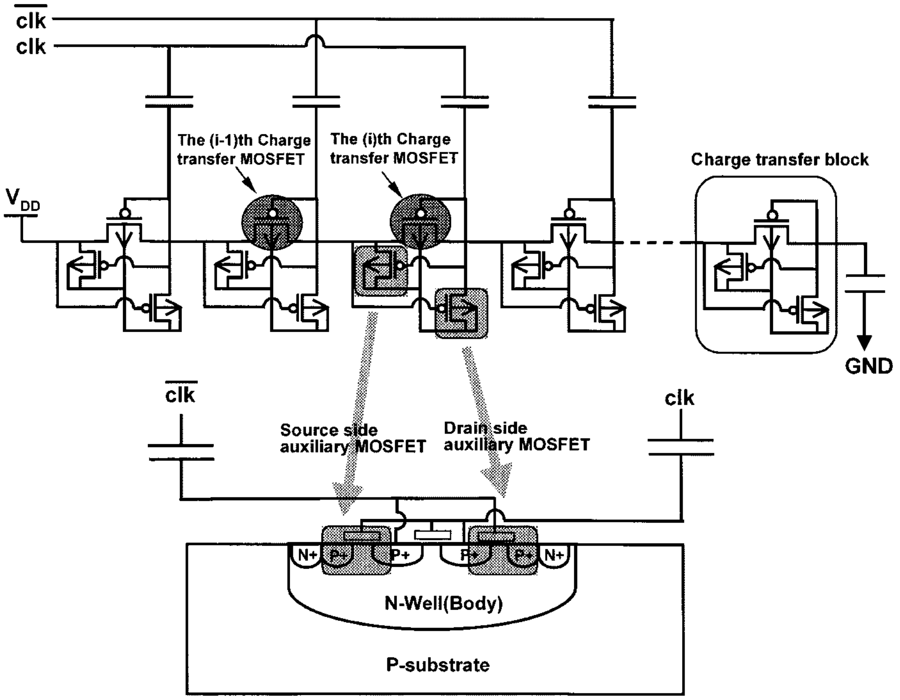

Fig. 2. Schematics and cross-section view of the proposed charge pump.

auxiliary MOSFET shares the drain with the charge-transfer MOSFET. For each charge-transfer block, two auxiliary MOSFET's and one charge-transfer MOSFET share the body which is separated from the body of other blocks. For the positive pumping, the proposed circuit is composed of only pMOSFET's, so that it can be made compact with little possibility of the latchup.

When the charge-transfer MOSFET is ON, the source-side auxiliary MOSFET always turns on. Then the source and the body of the charge-transfer MOSFET are connected through the source-side auxiliary MOSFET, so that no reverse bias exists between the source and the body of the charge-transfer MOSFET preventing threshold voltage increase. When the charge-transfer MOSFET is OFF, the drain-side auxiliary MOSFET turns on so that the drain and the body of the charge-transfer MOSFET are connected to prevent the body from floating.

In Fig. 2, when clk is low and $\overline{\text{clk}}$ is high, the ith charge-transfer MOSFET is ON and charges are transferred through it. At this moment, the source-side auxiliary MOSFET of the ith charge-transfer MOSFET turns on so that the source and the body of the ith charge-transfer MOSFET are connected. In this way, regardless of the pumped voltage, the threshold voltage of the ith charge-transfer MOSFET stays with V_{t0} (threshold voltage at zero back bias) during the charge transfer state. In this clock state, the $(i-1)$th charge-transfer MOSFET is OFF and the drain-side auxiliary MOSFET of the $(i-1)$th charge-transfer MOSFET turns on to connect the body and the drain of the $(i-1)$th charge-transfer MOSFET. When clk is high and $\overline{\text{clk}}$ is low, the proposed pump operates in the same manner as the previous state.

In the steady state, the source, drain, and body voltage of the ith charge-transfer MOSFET according to the clock state is shown in Fig. 3. As shown in the figure, the body voltage of the charge-transfer MOSFET keeps track of higher value of the source or the drain voltage at each clock state by the auxiliary MOSFET's.

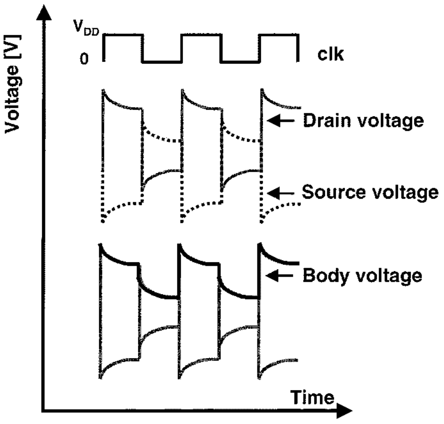

Fig. 3. Body voltage of the ith charge-transfer MOSFET in steady state.

In Fig. 4, the SPICE simulated output voltage of each charge pump for V_{DD} of 1.8 V is shown as the number of stage increases. It can be noted that the voltage gain in the Dickson charge pump reduces as the number of stage increases, whereas the newly proposed pump closely follows the ideal diode pump.

III. FABRICATION AND MEASUREMENTS

The proposed charge pump was fabricated with an 1.5-μm CMOS standard process. The thickness of the gate oxide is 25 nm and the values of threshold voltage V_{t0} are 0.73 V and − 0.7 V for nMOS and pMOS, respectively. The coupling capacitor and the output capacitor are formed by the gate oxide

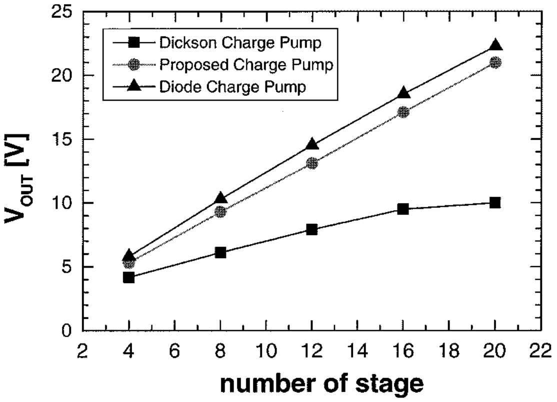

Fig. 4. Simulated output voltage of the diode charge pump, the Dickson charge pump, and the proposed charge pump as the number of stage increases. V_{DD} is fixed at 1.8 V.

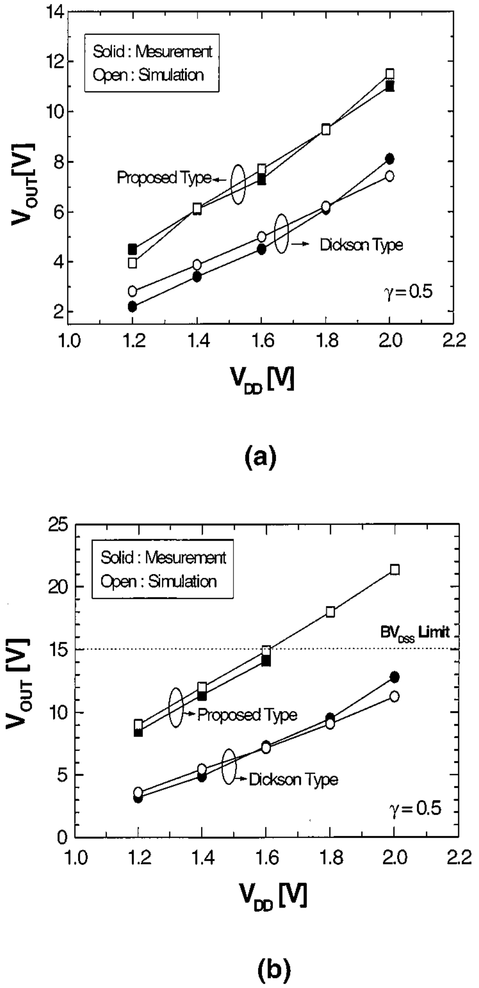

Fig. 5. Comparison of output voltage of the proposed charge pump and Dickson charge pump as V_{DD} increases (a) in 8-stage case and (b) in 16-stage case.

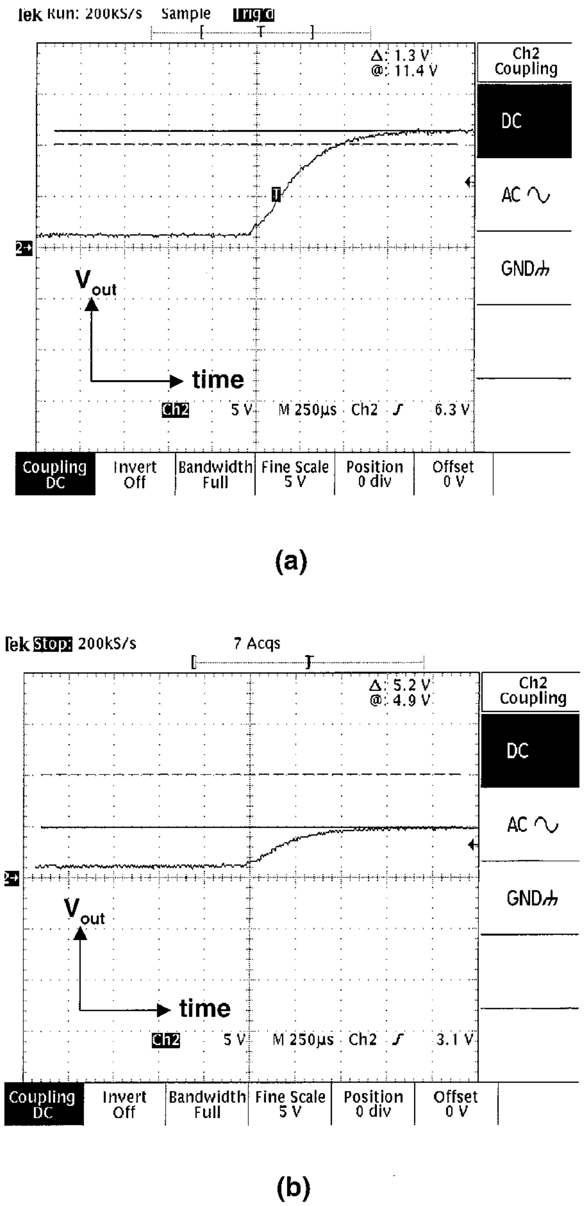

Fig. 6. Measured output voltage waveforms of (a) the proposed charge pump and (b) the Dickson charge pump with time axis. V_{DD} is 1.4 V and the number of stages is 16.

and the measured values are about 1 and 5 pF. The stray capacitance due to the substrate depletion region is about 0.25 fF/μm^2, which gives negligible contribution to the coupling capacitance for the well area used in this work. In order to reduce the well area, an n+/p+ butting structure is used. In Fig. 5(a) and (b), the simulated and measured output voltages of the fabricated Dickson charge pump and the proposed charge pump with 8 and 16 stages are shown as V_{DD} increases from 1.2 V to 2 V. For the ideal diode charge pump with no load, increase of ΔV in the supply voltage should cause $\Delta V \times (N+1)$ increase in the output voltage from (1). For $\Delta V = 0.2$ V and $N = 16$, the output voltage change ΔV_{out} of the diode charge pump is $0.2 \times 17 = 3.4$ V. In Fig. 5(b), the measured ΔV_{out} value of the proposed charge pump is 3.03 V, which is close to the ideal value considering the parasitic capacitance. For the Dickson charge pump, on the other hand, ΔV_{out} is only 1.91 V. The output voltage of the proposed charge pump with 8 stages has even higher output voltage than the Dickson charge pump with 16 stages. The voltage difference between the Dickson charge pump and the proposed pump becomes larger as the number of stage increases. It can be seen that while the Dickson charge pump with

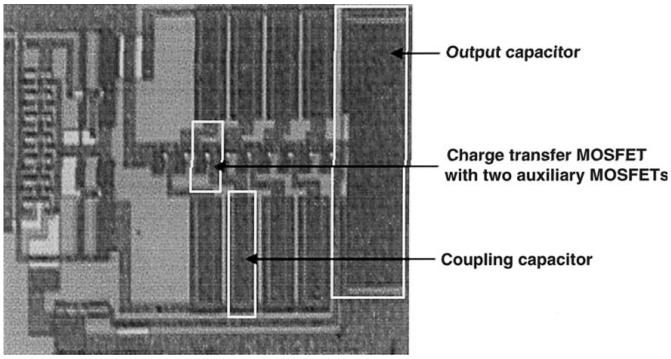

Fig. 7. Die photograph of the proposed charge pump.

16 stages has just a little increase in the output voltage from the pump with 8 stages, the output voltage of the proposed charge pump with 16 stages is almost double the output voltage of the pump with 8 stages.

In Fig. 6, the output voltage waveform of the proposed charge pump and the Dickson pump with 16 stages for V_{DD} of 1.4 V is shown, where higher voltage is obtained in the proposed circuit. The power consumption measured in the proposed 16-stage charge pump with 1-μA load current at V_{DD} of 1.4 V is about 0.23 mW. Its pumping frequency is 3 MHz. As shown in Fig. 7, the area penalty of the proposed charge pump by auxiliary MOSFET's is negligible since most of the area is occupied by the coupling and the output capacitors.

IV. CONCLUSION

A new charge pump has been realized by controlling the body voltage of MOSFET's. It has been shown that much higher output voltage than the Dickson charge pump is obtained by the newly proposed charge pump with variable body voltage. With two auxiliary MOSFET's, the body voltage is adjusted to remove the threshold voltage increase. By the SPICE simulation and measurement, it has been shown that the proposed charge pump successfully follows the performance of the ideal diode charge pump.

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