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Process-Variation-Adaptive Charge Pump Circuit using NEM (Nano-Electro-Mechanical) Relays for Low Power Consumption and High Power Efficiency

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***Abstract*—For some low-frequency applications such as power-related circuits, NEM relays have been known to show better performance than MOSFETs. For example, in a step-down charge pump circuit, the NEM relays showed much smaller layout area and better energy efficiency than MOSFETs. However, severe process variations of NEM relays hinder them from being widely used in various low-frequency applications. To mitigate the process-variation problems of NEM relays, in this paper, a new NEM-relay charge pump circuit with the self-adjustment is proposed. By self-adjusting a pulse amplitude voltage according to process variations, the power consumption can be saved by 4.6%, compared to the conventional scheme without the self-adjustment. This power saving can also be helpful in improving the power efficiency of the proposed scheme. From the circuit simulation of NEM-relay charge pump circuit, the efficiency of the proposed scheme is improved better by 4.1% than the conventional.**

***Index Terms*—Nano-electro-mechanical (NEM) relays, charge pump circuit, process-variation-adaptive, high power efficiency, low power consumption**

I. INTRODUCTION

Nano-Electro-Mechanical (NEM) relays have an ideal sub-threshold behavior, where the ‘off’ leakage current is almost zero [2]. NEM relays are composed of 4 terminals like MOSFET devices. However, in NEM relays, the mechanical channel is actuated by electrostatic force, instead of the electrical channel [2-6]. When the channel is turned off in NEM relays, it is disconnected mechanically from the both source and drain. By doing so, the ‘off’ leakage current can be ideally zero that is a very big advantage of NEM relays over MOSFET devices suffering a large amount of ‘off’ leakage. The demerit of NEM relays is that its electrostatic actuation of mechanical channel causes much longer switching time than the electrical channel’s fast switching time [3, 6]. Considering both the advantage and disadvantage of NEM relays, the NEM-relay circuits can be considered very suitable to applications that are energy-efficient and slow, such as power-related circuits [7, 8].

As one of low-frequency applications that can show better energy efficiency of NEM-relay circuits, a step-down charge pump circuit was designed and analyzed [7]. Here, the NEM relays and MOSFETs were compared in terms of layout area, power consumption, and power efficiency, etc. [7]. From the analysis, it can obviously be comprehended that the step-down charge pump with NEM relays has smaller layout area by more than one order of magnitude and higher power efficiency by more than 10%, than the MOSFET-based version [7].

In spite of smaller area and higher efficiency of the

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NEM-relay circuits, process variations of mechanical channel can be a serious problem in spreading NEM-relay circuits to wider applications. Even a small amount of variations in mechanical channel's dimensions can result in significantly large distribution of electrical parameters of NEM relays [2, 10]. For example, a 10% variation in the air gap of mechanical channel can make the largest pull-in voltage 3.6 times larger than the smallest pull-in voltage. The large amount of variations in electrical parameters, such as pull-in voltage, introduces a big burden to the circuit design, because it is important to satisfy all the possible cases including the worst case.

To avoid the burden of circuit design that is introduced by process variations, a new NEM-relay circuit with the self-adjustment function according to process variations is proposed, in this paper [12]. By doing so, the unnecessary power consumption can be minimized and the power efficiency can be much improved than the conventional scheme without the self-adjustment.

II. VERILOG-A MODEL AND PROCESS VARIATIONS OF NEM RELAYS

Fig. 1(a) shows the cross section of NEM relays that is composed of parallel-plate capacitor [2]. The capacitor has the movable gate electrode and the body, source, and drain electrodes that are fixed. The gate is mechanically controlled by a spring-like force and a damper-like force. The dynamic motion of the gate is calculated with the following equation [2].

$$\mathrm{F_{elec}(x) = mx'' + bx' + kx} \tag{1}$$

Here x is the displacement of the movable gate electrode. m is the gate's mass and b is the damping factor. k is the spring coefficient. F_{elec} is an electrostatic force which is caused by a voltage applied between the gate and body electrodes. g_0 is the actuator's gap between the gate and substrate. g_d is the dimple gap thickness.

The electrostatic force can be calculated with [1],

$$\mathrm{F_{elec}(x)} = \frac{\varepsilon_0 \times A_{ov} \times V_{gb}^2}{2\times(\mathrm{g_0\text{-}x})^2} \tag{2}$$

Here A_{ov} is the overlap area between the gate and body electrodes, ε_0 is the permittivity of free space, and V_{gb} is the voltage difference between the gate and body electrodes.

When a voltage applied between the gate and body electrodes is enough large to pull the gate to the body, the relay is turned on. The voltage needed to turn on the NEM relays is called the pull-in voltage, V_{pi}. It is expressed with [1]

$$\mathrm{V_{pi}} = \sqrt{\frac{8\times k\times g_0^3}{27\times\varepsilon_0\times A_{ov}}} \tag{3}$$

To turn off the NEM relay, a voltage called the release voltage, V_{rl}, should be applied to detach the gate from the body. The release voltage is expressed by [1]:

$$\mathrm{V_{rl}} = \sqrt{\frac{2\times(k\times g_d - F_A)\times(g_o - g_d)^2}{\varepsilon_0\times A_{ov}}} \tag{4}$$

Here, F_A is the surface adhesion force. When V_{rl} is applied to the NEM relays, the conducting path between the drain and source is physically detached. Thereby, the current can't flow through the channel after detaching it.

Comparing V_{pi} and V_{rl} in Fig. 1(b) shows that V_{rl} is smaller than V_{pi}. This is because detaching the gate electrode from the body should overcome not only the electrostatic force, but also the surface adhesive force. This voltage difference between V_{pi} and V_{rl} causes hysteretic switching characteristic in Fig. 1(b).

One important problem in NEM relays is the severe process variations. Especially, the geometrical dimensions such as g_0 and A_{ov} are suffering large amount of variations that can affect the pull-in voltage and release voltage very much, illustrated by the simulation results shown in Fig. 2(a)-(d). Fig. 2(a) shows the statistical variation of g_0, where the average is $1.8\text{x}10^{-7}$ m and the standard deviation is given 10%. Similarly, Fig. 2(b) shows A_{ov}'s distribution with the average value of $4.5\text{x}10^{-4}$ m^2 and 10% variation. The variations of g_0 and A_{ov} can affect the both pull-in voltage and release voltage, as shown in Fig. 2(c) and (d), respectively. Here, the average values of V_{pi} and V_{rl} are 3.5 V and 2.9 V, respectively. $V_{rl(min)}$ is the smallest value among all the V_{rl} values in Fig. 2(d). Similarly, $V_{rl(max)}$ is the largest

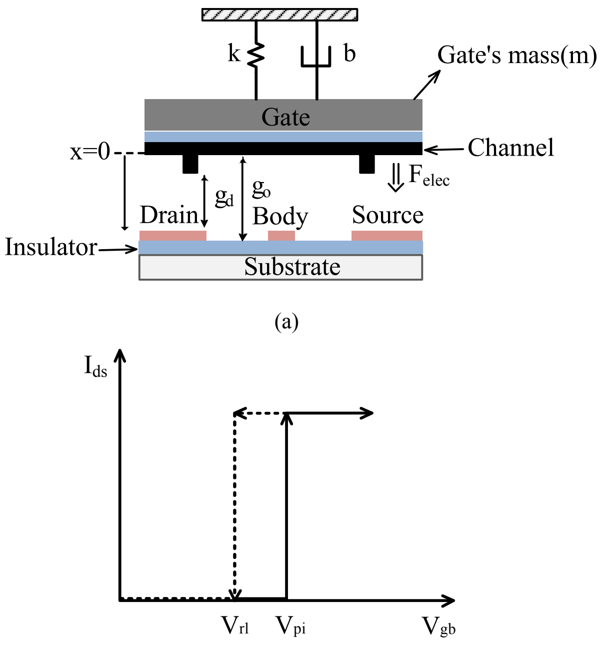


Fig. 1. (a) The cross section of NEM relays is composed of parallel-plate capacitor with the mass-spring-damper system [2], (b) The hysteretic swithcing characteristic of NEM relays shows different pull-in voltage and release voltage [7]

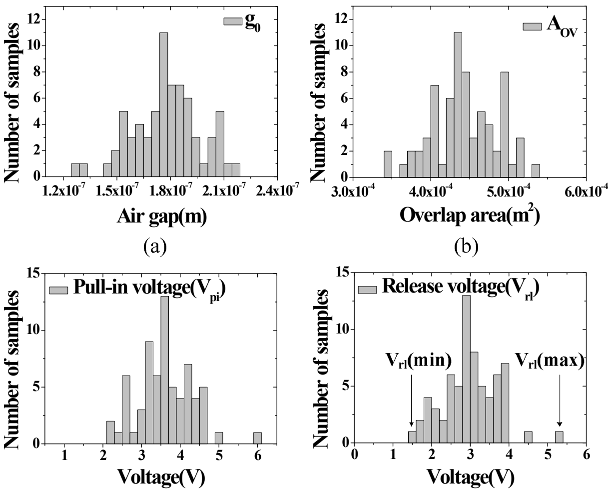


Fig. 2. (a) The statistical variation of g_0, where the average value is 1.8×10^{-7} m and the standard deviation is given 10%, (b) The statistical variation of A_{ov}, where the average value is 4.5×10^{-4} m^2 and 10% variation is given, (c) The statistical variation of V_{pi} that are caused by the variations of g_0 and A_{ov} in Fig. 2(a) and (b), respectively, (d) The statistical variation of V_{rl} that are caused by the variations of g_0 and A_{ov} in Fig. 2(a) and (b), respectively

value in the variation in Fig. 2(d). In Fig. 2(d), $V_{rl(min)}$ and $V_{rl(max)}$ are 1.55 V and 5.45 V, respectively.

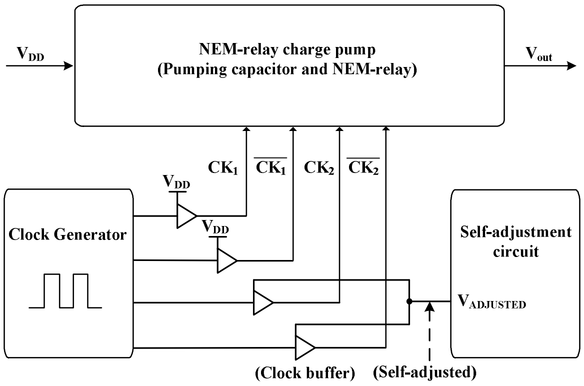


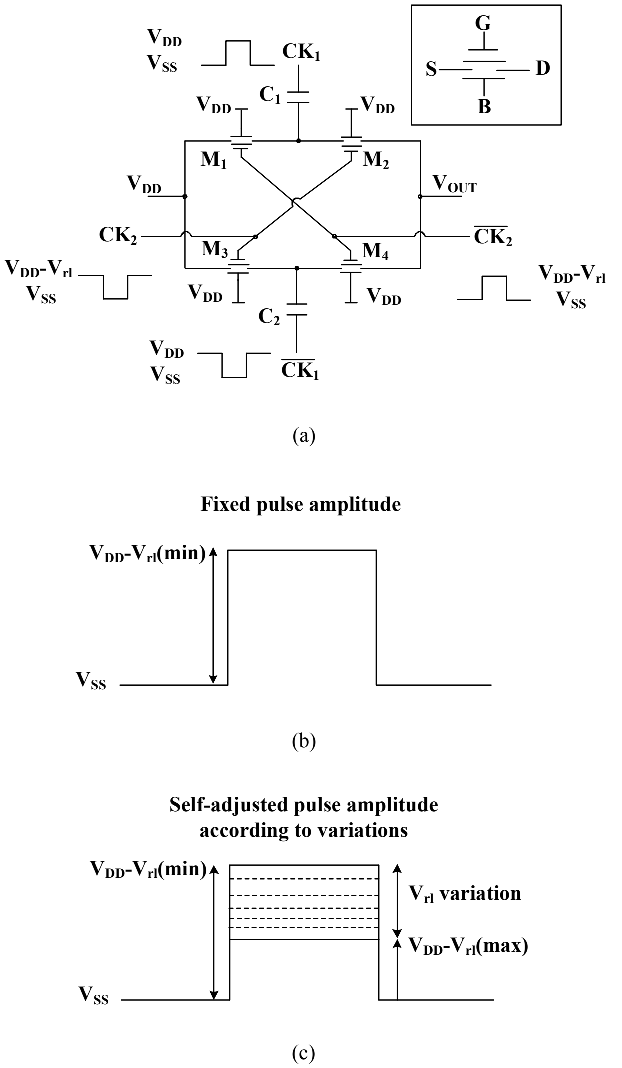
Fig. 3. The block diagram of the proposed NEM-relay charge pump circuit with the self-adjustment. The adjusting circuit can adjust the pulse amplitude of CK_2 and $/CK_2$ to minimize switching power consumption in controlling the relays

III. THE PROPOSED NEM-RELAY CIRCUIT WITH THE SELF-ADJUSTMENT ACCORDING TO PROCESS VARIATIONS

As mentioned in the introduction part, the NEM-relay charge pump circuit can have smaller layout area and better power efficiency due to the advantage of mechanical channel of NEM relays over the electrical channel of the conventional MOSFETs. However, large process variations of NEM relays can hinder the NEM-relay circuits from being widely used in practical applications. To mitigate these process-variation-related problems of NEM relays, a simple self-adjustment circuit that can adjust the pulse amplitude voltage according to process variations is proposed in this paper.

Fig. 3 shows a block diagram of the NEM-relay charge pump circuit with the self-adjustment which can adjust the pulse amplitude of clock signals according to process variations. In Fig. 3, the switching power consumption of NEM-relay charge pump circuit can be minimized by the self-adjustment at a given process-variation condition. V_{DD} is the input supply voltage. V_{OUT} is the output voltage of NEM-relay pump circuit. CK_1 and $/CK_1$ are generated from the clock generator to drive the pumping capacitors. CK_2 and $/CK_2$ are to control the relays. In Fig. 3, the adjusting circuit can change the pulse amplitude of CK_2 and $/CK_2$ according to process variations to minimize the switching power loss in controlling the relays.

Fig. 4(a) shows the NEM-relay charge pump circuit. M_1, M_2, M_3, and M_4 are NEM relays. C_1 and C_2 are



(a)

(b)

(c)

Fig. 4. (a) The NEM-relay charge pump circuit, (b) The conventional scheme, where the pulse amplitude of CK_2 and $/CK_2$ is fixed by V_{DD}-$V_{rl(min)}$ of the worst-case of V_{rl} variation, (c) The proposed self-adjustment scheme, where the pulse amplitude of CK_2 and $/CK_2$ is self-adjusted according to the process variation of V_{rl}

pumping capacitors. CK_1 and $/CK_1$ are the true and inverted versions of clock signal for driving pumping capacitors. CK_2 and $/CK_2$ are the true and inverted versions of clock signal for controlling the NEM relays. The NEM-relay charge pump circuit can deliver the output voltage, V_{OUT}, as high as $2V_{DD}$. The NEM relay has 4 terminals which are the gate, source, drain, and body, as shown in the inset of Fig. 4(a). Here, the body electrode of NEM relay is applied by V_{DD}. If the gate electrode is applied by 0V, the NEM relay is turned on with $|V_{gb}|=V_{DD}$. If the gate electrode has a voltage of V_{DD}-V_{rl}, the relay is turned off with $|V_{gb}|<=V_{rl}$.

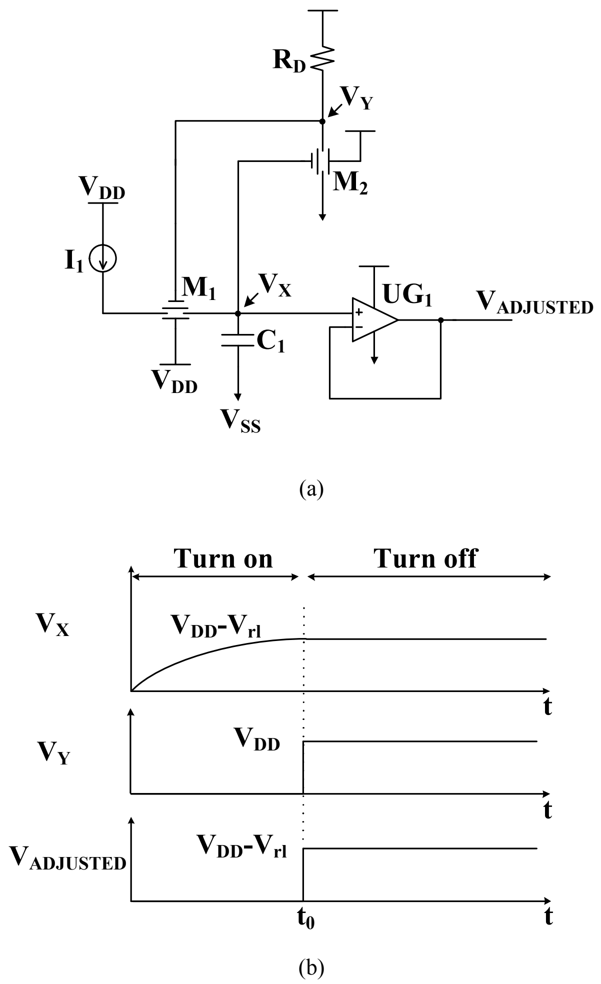
To explain the concept of self-adjustment of pulse amplitude of clock signals, let us go back to Fig. 2(c) and (d), where the pull-in and release voltages seem to suffer severe process variations. To turn off NEM relay, V_{gb} should be as small as V_{rl}. Considering the V_{rl} variation in Fig. 2(d), V_{gb} should be as small as $V_{rl(min)}$. In this worst-case scenario, the pulse amplitude of CK_2 and $/CK_2$ should be fixed by V_{DD}-$V_{rl(min)}$, as shown in Fig. 4(b). This fixed amount of pulse amplitude as high as V_{DD}-$V_{rl(min)}$ can be a waste for the rest of V_{rl} values that are larger than $V_{rl(min)}$. Considering the case of $V_{rl(max)}$, the pulse amplitude can be as low as V_{DD}-$V_{rl(max)}$ to turn off NEM relays and, thereby more switching power can be saved.

The self-adjustment circuit can adjust the pulse amplitude of CK_2 and $/CK_2$ according to the V_{rl} variation, as shown in Fig. 4(c). For $V_{rl(max)}$ in Fig. 2(d), the pulse amplitude can be lowered to V_{DD}-$V_{rl(max)}$. For $V_{rl(min)}$ in Fig. 2(d), the amplitude is decided as high as V_{DD}-$V_{rl(min)}$. By adjusting the pulse amplitude according to the V_{rl} variation, the switching power consumption in the V_{rl} variation can be minimized.

Fig. 5(a) is the self-adjustment circuit for adjusting the pulse amplitude of CK_2 and $/CK_2$. M and M_2 are NEM relays. I_1 is the constant current source. C_X is the charging capacitor. UG_1 is the unit gain buffer. The waveforms of important signals are shown in Fig. 5(b). At the initial time, V_X is discharged to 0V. V_Y is also 0V because M_1 is turned on at the initial moment. At this time, M_2 is turned on by V_Y=0V. As I_1 is accumulated on C_X, V_X is increased higher. When V_X becomes high enough to release the gate from the body in M_1, M_1 becomes ‘off’. At this time, V_Y becomes high to turn off M_2. By turning off M_2, the V_X voltage as high as V_{DD}-V_{rl}, at the releasing moment can be retained on C_X for long time. This V_{DD}-V_{rl} is delivered to the NEM-relay charge pump circuit by the unit gain buffer, UG_1.

IV. SIMULATION RESULTS

The conventional and proposed schemes were compared in terms of power consumption and power efficiency as shown, in Fig. 6(a) and (b). The simulation was implemented through Cadence Spectre [13]. The NEM relays were modeled using Verilog-A and DONGBU HITEK 0.18-μm CMOS parameters were



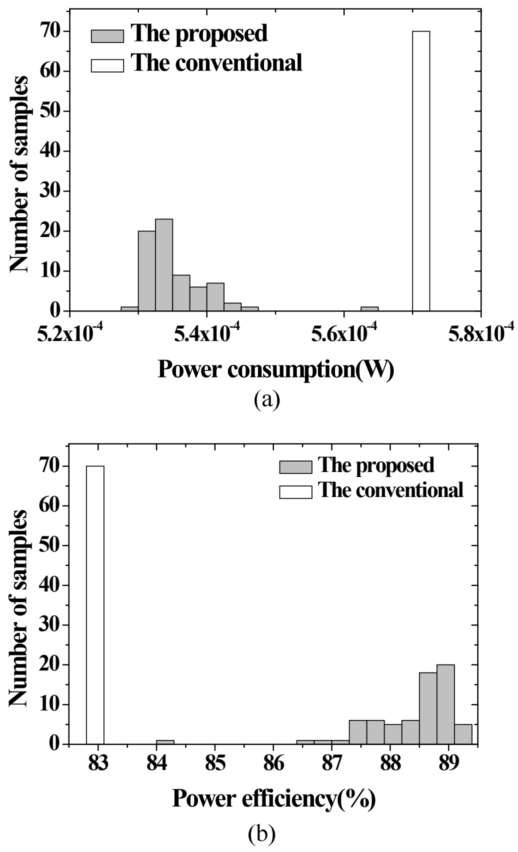
(a)

(b)

Fig. 5. (a) The self-adjustment circuit for adjusting the pulse amplitude of CK_2 and $/CK_2$ according to the V_{rl} variation to minimize the switching power consumption, (b) The waveforms of V_X, V_Y, and $V_{ADJUSRED}$

used in the simulation. For the power consumption, the conventional scheme without the self-adjustment circuit consumes 571 μW in Fig. 6(a). The proposed scheme with the self-adjustment circuit can reduce the power consumption from 571 μW to 545 μW in average in Fig. 6(a). The percentage power saving is improved by as much as 4.6% in the proposed scheme due to self-adjusting the pulse amplitude according to V_{rl} variation. The power efficiency is compared in Fig. 6(b). The power efficiency of the conventional scheme is as low as 82.8%. Due to the self-adjustment, the efficiency of the proposed scheme can be improved by 86.9%.

The power overhead that is consumed by this self-adjust circuit in Fig. 5(a) is as small as 1.65% in the power consumption of NEM-relay charge pump circuit.



(a)

(b)

Fig. 6. (a) Power consumption of the conventional scheme without the self-adjustment and the proposed scheme with the self-adjustment, (b) Power efficiency of the conventional scheme without the self-adjustment and the proposed scheme with the self-adjustment

The area penalty of the self-adjustment circuit can be neglected, because most of layout area of the charge pump circuit is occupied by the pumping capacitors and pumping switches in Fig. 4(a). Comparing to the charge pump circuit with these large-area pumping capacitors and pumping switches, the self-adjustment circuit can be designed with the smaller-size devices and capacitors. In this paper, the pumping capacitors of C_1 and C_2 in Fig. 4(a) are assumed as large as 60pF, while C_X in Fig. 5(a) is as small as 1pF. It means that the area of the self-adjustment circuit can be as small as 1/60 of the charge pump circuit.

V. CONCLUSIONS

For some low-frequency applications such as power-related circuits, NEM relays have been known to show better performance than MOSFETs [7, 8]. For example, in step-down charge pump circuit, the NEM relays showed much smaller layout area and better energy efficiency than MOSFETs [7, 8]. However, severe process variations of NEM relays hinder them from being widely used in various low-frequency applications.

To mitigate the process-variation problems of NEM relays, the new NEM-relay charge pump circuit with the self-adjustment was proposed in this paper. By adjusting the pulse amplitude according to process variations, it was possible to save the power consumption by 4.6%, compared to the conventional scheme without the self-adjustment. This power saving could also be helpful in improving the power efficiency of the proposed scheme. From the circuit simulation of NEM-relay charge pump circuit, the efficiency of the proposed scheme was improved better by 4.1% than the conventional.

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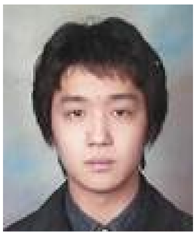

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