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Low-voltage cold-start circuit for energy harvesting suitable for indoor sunlight

Jiaju Pan*, Xinning liu, Dengbang Yu

National ASIC System Engineering Technology Research Center,Southeast University, Nanjing 210096,China

Corresponding author’s e-mail: 220184818@seu.edu.cn

Abstract. This paper proposes a low-voltage cold-start circuit suitable for indoor sunlight energy harvesting in TSMC 40nm CMOS process. The circuit can work normally when the input voltage is as low as 200mV and is compatible with a wide input power range. Pulse-skipping modulation (PSM) is used to control the circuit's operation and sleep. The main structure includes a ring oscillator, a two-phase clock drive circuit, a linear charge pump, a low-power voltage reference, and a hysteresis comparator. Compared with other cold-start circuits, the structure proposed in this paper can realize the function of voltage rise without the aid of external machinery or voltage. Simulation results show that when the input voltage is in the range of 200mV to 700mV, the cold-start circuit can stably output 800mV to power the subsequent circuit.

1. Introduction

In recent years, the intelligent nodes of the Internet of Things have developed rapidly, with smaller and smaller volumes, and more and more powerful functions, which can be applied to the fields of smart home, environmental testing, smart cities, etc. Energy harvesting circuit (EH) can achieve long-term work of intelligent nodes by collecting external energy, which has become a hotspot for extensive research [1].Solar energy is an ideal energy source due to the advantages of output energy density and voltage amplitude. However, when it comes to rainy weather or working indoors, the energy harvesting circuit needs to achieve effective energy harvesting in low light, which is a big challenge[2].

The cold-start circuit is an important part of the energy harvesting system which is used to perform the preliminary voltage rise to enable the main boost module to obtain the power supply voltage. The input voltage of a cold-start circuit used in solar energy collection is determined by the output voltage of a solar photovoltaic cell. Due to the change in sunlight intensity, the input voltage will fluctuate to a certain degree. The traditional cold-start circuit is only suitable for outdoor bright light scenarios, and the input voltage is above 500mV. Therefore, it cannot work normally in rainy weather or indoor low-light scenes, and requires voltage or mechanical assistance[3][4]. In practical applications, the output voltage of photovoltaic cells is between 200mV-700mV. Within this voltage range, the output power will experience fluctuations of 10uW-10mW. This requires a cold-start circuit to not only complete the function of voltage rise at low input voltage, but also to meet the wide range of output power requirements of photovoltaic cells.

This paper proposes a low-voltage cold-start circuit for energy harvesting suitable for indoor sunlight, which can meet the input voltage as low as 200mV to achieve normal work without the aid of voltage or mechanical assistance and is compatible with a wide input power range. The circuit modules mainly include: ring oscillator, two-phase clock driving circuit, linear charge pump, low power consumption voltage reference, hysteresis comparator, etc.

This paper is organized as follows: Section 2 presents the low-voltage cold-start circuit proposed in this article in detail. Section 3 summarizes the simulation results. Section 4 concludes the work of the paper.

2. Proposed cold-start circuit

2.1 Main structure

The cold start circuit is shown in Figure 1. The main structure is composed of a ring oscillator circuit, a two-phase clock drive circuit, a linear charge pump circuit, a low power voltage reference circuit, and a hysteresis comparator circuit.

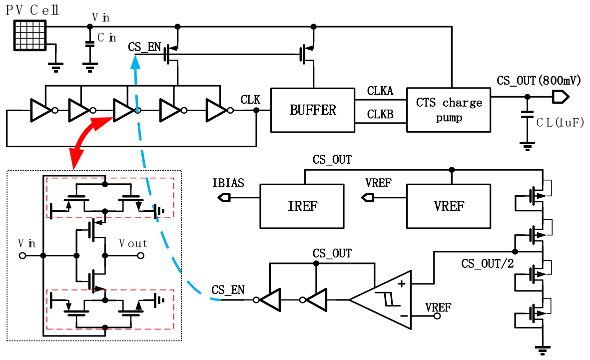

Figure 1. Main structure of cold-start circuit

The circuit uses PSM modulation to switch the working mode, so that the system can work stably and effectively. As shown from figure 1, this structure uses a ring oscillator circuit to generate the system operating clock CLK, then the two-phase clock drive circuit generates two-phase non-overlapping signals CLKA and CLKB to drive the linear charge pump. Finally, the linear charge pump charges the off-chip energy storage capacitor CL and raises the input voltage to 800mV output. The diode-connected PMOS series constitutes a voltage divider circuit to divide the output voltage to obtain CS_OUT/2. The low-power voltage reference and current reference provide the voltage reference VREF and the tail current IBIAS for the hysteretic comparator. When CS_OUT/2 rises above VREF to reach the hysteresis of the flip, the hysteresis comparator output signal flips from a low level to a high level. After the output signal is shaped and driven by the two-stage inverter, a cold start enable signal CS_EN is obtained, and this signal is applied to the gates of the enable PMOS transistors, thereby closing the ring oscillator circuit and the two phases during the cold start. At this time, the cold-start circuit enters the sleep mode.

When the cold-start circuit is in sleep mode, the linear charge pump no longer charges the off-chip energy storage capacitor CL, and the output voltage value will decrease over time. When the value of CS_OUT/2 drops below VREF and reaches the hysteresis amount of the hysteresis comparator's downward flip, the comparator output signal flips from high to low. CS_EN signal also flips to low level and acts on the gates of the enable PMOS transistors. At this time, the ring oscillator circuit and the two-phase clock driving circuit are turned on, the cold start circuit enters the working mode again, the linear charge pump works, charges the off-chip energy storage capacitor, and raises the output voltage to 800mV.

This circuit enables the energy harvesting system to work at an input voltage as low as 200mV. When the first-stage output voltage is raised, the cold-start circuit enters sleep mode to prevent the output voltage from being too high to cause damage to the cold-start internal circuit and reduce the power consumption of energy harvesting system. Compared with other cold-start circuits, this structure can replace the voltage or external mechanical assistance to complete the self-starting and self-powering functions of the energy harvesting circuit. No additional battery power is required for energy harvesting, and the charge energy converted by photovoltaic cells is stored in supercapacitors or batteries.

2.2 Linear Charge pump

The main purpose of the cold start circuit is to raise the input voltage, that is, to complete the conversion process from DC voltage to DC voltage. Commonly used DC-DC conversion circuits include linear regulator (LDO), switched inductive DC-DC, and switched capacitor DC-DC. Switched-capacitor DC-DC can realize both step-up and step-down conversion, and its small size is suitable for low-voltage application conditions that need to compromise efficiency and area. In summary, the low-voltage cold-start circuit uses a switched-capacitor boost circuit, that is, a linear charge pump to convert the input voltage. Figure 2 shows the structure of a linear charge pump[5].

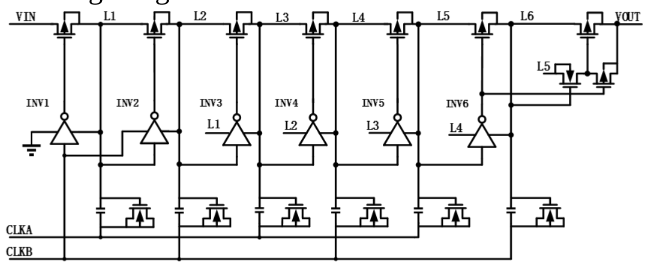

Figure 2. Six-stage linear charge pump

The six-stage linear charge pump (LCP) used in this paper is an improvement of the dynamic charge transfer switch (CTS) charge pump. As shown in the figure, the linear charge pump is driven by two-phase clocks CLKA and CLKB. The dynamic inverter is used to control the gate voltage of the P-type CTS. The MOM capacitor is connected in parallel with the MOS capacitor to increase the capacitance density. When CLKA = 0, MP41, MP43, MP45, MP47 are turned on, MP42, MP44, MP46 are turned off. At this time, VIN charges C41, and the even-stage capacitor of the previous stage charges the odd-stage capacitor of the next stage. When CLKA = 1, MP42, MP44, MP46 are turned on, MP41, MP43, MP45, MP47 are turned off. At this time, the odd-numbered capacitor of the previous stage charges the even-numbered capacitor of the latter stage.

For each stage of the dynamic inverter, its input stage is connected to the output stage of the previous stage, and the output stage is connected to the P-type CTS gate of this stage to control the conduction and close of the CTS. The gates of the NMOS and PMOS of the inverter of the last stage are respectively connected to the output of the previous stage and the CTS gate of the previous stage. The advantage of adopting this scheme is that when the VDD is low, the structure of using the dynamic inverter to control the CTS gate voltage cannot guarantee the full turn-on of the PMOS, so it cannot guarantee that the final CTS is completely turned off, and the output will have a charge leakage. By connecting the gate of the PMOS to the gate of the previous stage CTS, a sufficient gate-source voltage can be obtained, so as to ensure that the CTS of this stage is completely turned off.

2.3 Low power voltage reference

The voltage reference circuit provides a reference voltage for the hysteresis comparator and is powered by the output voltage of the linear charge pump. In the cold-start circuit, the output voltage is only 800mV, which makes the design of the voltage reference more difficult. The voltage reference proposed in this article uses a low-power design and can work normally when the supply voltage is as low as 800mV[6].

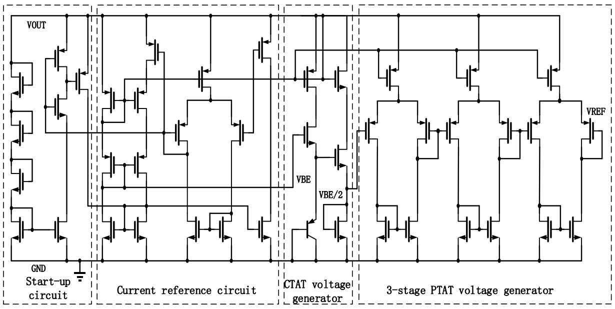

Figure 3. Low power voltage reference

As shown from figure 3, the low-power voltage reference circuit consists of four parts: a start-up circuit, a self-bias circuit, a CTAT voltage generation circuit, and a 3-level PTAT voltage generation circuit. The CTAT voltage generating circuit and the 3-level PTAT generating circuit are used as main parts to generate a reference voltage VREF with zero temperature coefficient at the output. The self-bias current generating circuit provides a bias current for the reference circuit, and the start-up circuit ensures that the circuit works normally. The CTAT voltage generating circuit uses the negative temperature coefficient of the BJT transistor base-emitter voltage (VBE), and then generates a negative temperature coefficient voltage of VBE/2 at the MN513 drain stage through the voltage division of NMOS series.

The 3-stage PTAT voltage generating circuit uses the characteristic of the positive temperature coefficient of the gate voltage difference (VGG) of the MOS transistor operating in the subthreshold region.

$$\begin{aligned} V_{GG} &= V_{GS2} - V_{GS1} \\ &= V_{TH} + \eta V_T \ln\left(\frac{I_{D2}}{K_{D2} I_O}\right) - V_{TH} - \eta V_T \ln\left(\frac{I_{D1}}{K_{D1} I_O}\right) \\ &= \eta V_T \ln\left(\frac{K_{D1} K_{M2}}{K_{D2} K_{M1}}\right) \end{aligned} \tag{1}$$

Where K_{D1} and K_{D2} are the aspect ratios of the differential pair in the single PTAT voltage generating circuit, and K_{M1}& K_{M2} are the aspect ratios of the current mirror transistors. The three-stage connection is then used to enhance the positive temperature coefficient to produce the required PTAT voltage. So, we can get the reference voltage output expression:

$$V_{REF} = \frac{V_{EB}}{2} + 3\eta V_T \ln\left(\frac{K_{D1} K_{M2}}{K_{D2} K_{M1}}\right) \tag{2}$$

2.4 Low voltage ring oscillator

The ring oscillator circuit module uses a low voltage structure to provide clock drive for the subsequent charge pump. Different from the traditional ring oscillator, the inverter delay unit in the low-voltage ring oscillator circuit uses a stacked inverter, as shown in the figure:

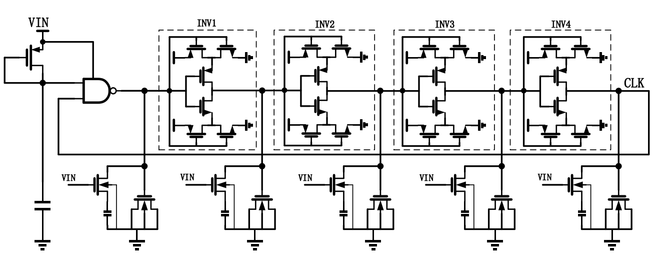

Figure 4. Low voltage ring oscillator

As a clock module in a cold start circuit, the ring oscillator circuit uses a lower input voltage as the power supply voltage, which brings two major problems[7].First, the lower supply voltage reduces the gain of the inverter, thereby reducing the ability of the ring oscillator to start and maintain oscillation. Second, the lower supply voltage compresses the output clock swing. This article uses a stacked inverter to replace the traditional inverter in the circuit structure, thereby effectively solving the above problems. On the one hand, Stacked inverters increase the gain of the inverter delay unit, thereby enhancing the ability of the ring oscillator to maintain oscillation at low supply voltages. On the other hand, the stacked inverter allows the output voltage to be extended when the load capacitor is charged and discharged which increase the output voltage swing.

3.Simulation results

Figure 5 is the layout of the cold-start circuit, the capacitor in the six-stage linear charge pump occupies a large area. Figure 6 is a function and working mode illustration. As we can see, when CS_EN is high, the circuit enters the sleep mode and the output voltage drops. When CS_EN is low, the circuit is in working mode, and the output voltage is raised to complete the start function. Figure 7 is a cold-start output diagram under different voltages. Figure 8 is the final output simulation diagram of the cold-start circuit. The simulation result is basically the same as the function diagram, which realizes the cold start purpose. Table 1 shows the comparison of indicators. It can be seen from the table that although [3], [4] achieve lower starting voltages, these two schemes rely on mechanical or voltage assistance, respectively, which increase the cost of the chip. In [8], the charge pump is used to raise the voltage, but the minimum input voltage is 220mV, which is not fully compatible with indoor sunlight. Although [9] can work at 129mV, the start-up time is too long.

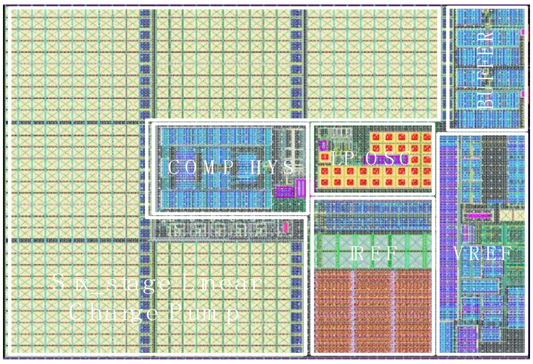

Figure 5. Layout of proposed cold-start circuit

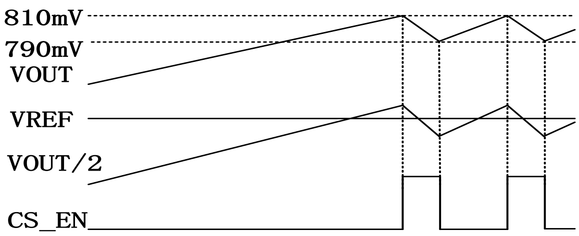

Figure 6. Function and working mode illustration

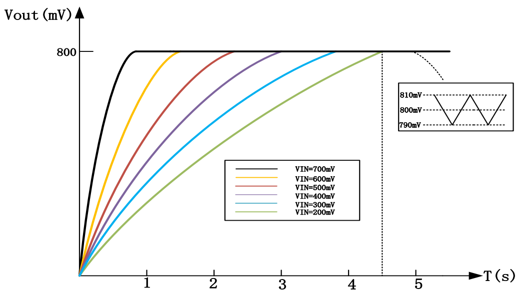

Figure 7. Output curve graph under different Input voltages

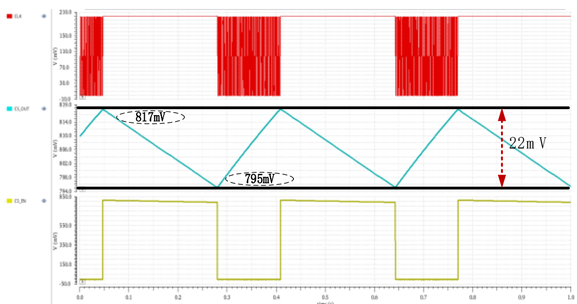

Figure 8. Simulation results

Table 1. Comparison of design indicators

References	**JSSCC11 [3]**	**JSSCC10 [4]**	**JSSCC15 [8]**	**ISSCC19 [9]**	**This work**
Process	***0.35um***	***0.13um***	***0.13um***	***0.18um***	***40nm***
Start-up mechanism	Mechanical assistance	Voltage assistance	Charge pump	Charge pump	Charge pump
Cold-start voltage	35mV	20mV	220mV	129mV	200mV
Start-up time	18ms	N/A	3.5s	150s	4.5s

4.Conclusion

This paper presents a low-voltage cold-start circuit that can be applied to an energy harvesting system where indoor sunlight is used as an energy source. This circuit can complete the start function when the input voltage is as low as 200mV, and does not rely on traditional voltage or mechanical assistance. The cold start circuit further amplifies the solar photovoltaic voltage collected in the room as the power supply voltage of the subsequent circuit. The simulation results show that when the input voltage is between 200mV-700mV, the cold-start circuit can convert it into a stable 800mV voltage output, and the start-up time is about 4.5s.

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