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Low Voltage Charge Pump for RF Energy Harvesting Applications

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Abstract

Objective: As the need for energy increases, new technologies should replace the conventional energy resources. Energy harvesting is one of these technologies and finds applications in many areas such as wireless sensor networks, biomedical applications. Findings: This paper presents a low-voltage charge pump which works at input voltage as small as 100 mV and is suitable for wireless energy harvesting applications. With 100 mV input, the proposed charge pump provides an output of 1.05 V. This output voltage is adequate for charging low power devices for biomedical applications and wireless sensor networks. Novelty/Improvement: The proposed charge pump has the voltage conversion ratio (M) greater than 10 and the circuit does not need any start-up voltage mechanisms for the operations. Method/Analysis: The result presented in this work is based on extensive simulation on SPICE and are experimentally validated CNFET model of Stanford University.

Keywords: Charge Pump, Clock Generator, CNFET, Energy Harvesting

1. Introduction

Nowadays, the uses of wireless portable devices have grown in many applications such as mp3 players, cell phones or sensor networks. Batteries are the main source of power for such devices. But the use of batteries has led to the increase in weight and requires frequent replacements. In applications such as wireless sensor nodes where several sensor nodes are dispersed over vast region, it becomes impractical to change the batteries when they get depleted. Also in applications in medically implantable devices, replacement of batteries is impossible. Therefore, the use of batteries for powering such devices is absurd.

Energy harvesting techniques make use of energies from the surrounding environment to supply power to the integrated circuits. Energy harvesting/scavenging techniques are the area of interest for powering wireless portable devices and wireless sensor networks[1,2]. Energy is widely distributed everywhere around us. The energy from sunlight (solar), energy from wind, energy from earth's heat (geothermal), energy from electromagnetic waves (radio frequency), etc, are the wide examples of these renewable energies. However, the energy from these kinds of sources goes unutilized or wasted. Using a technology known as Energy harvesting, such kind of energies are harvested and conditioned into usable form. Energy harvesting is the need of today's world especially in applications such as biomedical operations such as body sensor networks and remote area monitoring wireless sensing networks. However the energy harvested from these conventional energy sources are relatively very low. This small amount of energy cannot be used directly for any viable purpose. However if this harvested energy can be boosted via a signal conditioning circuit consisting

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of a DC to DC up converter/booster circuit, the output voltage can be stored on a capacitor, super capacitor or can directly charge the battery. Autonomous devices self-powered over full lifetime are critical for portable applications and structural health monitoring. Recently, Energy harvesting circuits are getting much attention for charging ultra-low power integrated circuits such as implantable biomedical sensors and Wireless Sensor Nodes (WSNs) for remote monitoring applications and where replacement of batteries are very difficult.

For making low voltage energy scavenging feasible, suitable voltage step-up circuits is needed. Charge pump are DC-DC converter circuits that increase the power supply voltage (V_{DD}) to some higher DC voltages. Charge pump use capacitors to transfer the charge from supply voltage terminal to the output terminal and use transistors as switches to generate the required voltage level. Charge pump find applications in systems that require different voltage levels for different functional blocks such as flash memories, EEPROM, DRAM and several driver circuits.

The circuit presented in[3] is able to step-up a 200 mV supply voltage to high voltage of 1.2 V but it requires hybrid inductive and capacitive architecture. In[4] authors have introduced a RF based charge pump which up-converts an input signal of 300 mV to 1 V. Some other related works are also available in literatures which operate at very small voltage lesser than 100 mV but need additional external circuitry as high as 650 mV[5]. In[6] a carbon nanotube based DC to DC converter has been suggested which steps-up 100 mV voltage signals to 650 mV. Recently in[7], authors boost 150 mV radio-frequency signals to 1 V but have used an electrical start-up mechanism. The circuit proposed in this paper works at input voltage as low as 100 mV and is based on carbon nanotube based technology and it also does not need an external start-up voltage or mechanical switch to start the operation.

The remaining paper is arranged as follows: Section 2 discusses the carbon nano-tube based FET. Section 3 introduces the architecture of the proposed charge pump. Section 4 demonstrates the result and Section 5 gives the conclusion.

2. CNFET

A novel charge pump design is introduced which comprises Carbon nano-tube based FET for up-conversion of the small input voltage. CNFETs have emerged as the state-of-the-art devices which overcome the disadvantages of conventional CMOS technology. CMOS technology is reaching its scaling capabilities at channel lengths below 45-nm. Moore's "law" is explained as doubling of transistor performance and quadrupling of number of transistors on chip every three years. But due to excessive scaling, MOSFETs suffer from serious challenges like subthreshold leakage current, extreme short-channel effects, S/D-to-substrate band-to-band tunneling, process variations and lithographic limitations. Several renovations have been presented in the literature such as Fin FETs, Dynamic threshold MOSFET, Ultra-thin body single or multiple-gate FETs, Silicon on insulator FETs and Strained-silicon FETs to contribute advancements over classical CMOS devices. But to maintain the saturating Moore's law, Carbon Nanotube based FET (CNFET) technology is preferred as the most appropriate for extending or complimenting the conventional MOSFET technology[7]. Nonetheless, problems of CNFET fabrication have been resolved and therefore as the technology reaches its maturity, CNFET will certainly rule the market[8].

Conventional MOS transistor employs bulk silicon for their semiconducting channels. Carbon nano-tubes based FET, on the other hand, uses carbon nanotubes for their semiconducting channels instead of bulk silicon as shown in Figure 1 and Figure 2. Carbon nanotubes use sheet of graphene rolled into hollow cylinder of diameters ranging from 0.4 nm to 4 nm. Based on their diameters, CNTs are categorized as, SWCNT (single-walled carbon nanotube) and MWCNT (multi-walled carbon nanotube). SWCNT diameter is close to 1 nm whereas if multiple CNTs with different diameter are concentrically rolled inside one another, the resulting configuration is multi-walled carbon nanotube (MWCNT)[9]. MWCNT diameter ranges from several nm to tens of nm. SWCNTs can either be semiconducting or metallic (conductor) and depend on the angle (chirality integer vector (n_1, n_2)) in which they are rolled. For a metal nanotube, $n_1 = n_2$ or $n_1 - n_2 = 3i$; where i is an integer. Otherwise the Carbon nanotube is semiconducting. The relationship between chirality (Ch), diameter of CNT (D_{CNT}) and device threshold (V_T) is given by[10,11]:

$$Ch = a\sqrt{n_1^2 + n_2^2 + n_1 n_2} \quad (1)$$

$$D_{CNT} = \frac{Ch}{\pi} \quad (2)$$

$$V_T = \frac{E_g}{2e} = \frac{aV_\pi}{eD_{CNT}\sqrt{3}} \quad (3)$$

Where e is electron charge, E_g is the band gap energy, V_π is the carbon π-π bond energy and is 3.033 eV, $a = \sqrt{3}d = 2.49$ Å is the lattice constant (where d = 1.44 Å is the inter carbon atom distance).

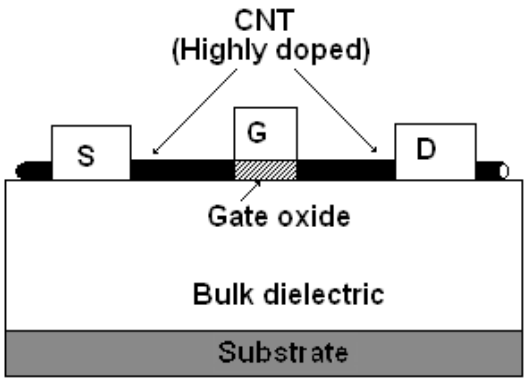

Figure 1. Cross sectional view of CNFET structure.

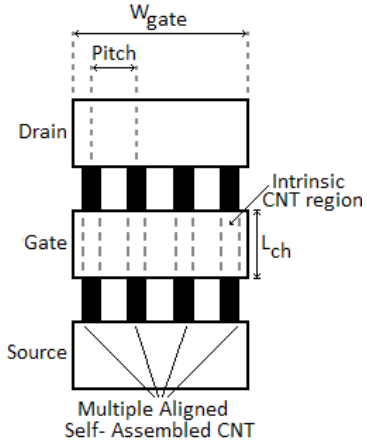

Figure 2. Top view of CNFET structure.

By virtue of its remarkable electrical and physical characteristics, the carbon nanotube devices can replace the traditional silicon based devices. The CNFET also offers higher drive current, larger transconductance than MOSFET. The charge pump circuit introduced here consists of carbon nano-tube transistors. Due to the use of CNFET, the losses are minimized and the device can operate below 100 mV with lower on resistance and negligible off-current. Based on Equation (3), it can be seen that the device threshold (V_T) of a carbon nano-tube transistors is varied by changing the diameter (D_{CNT}) of the tubes. This enables CNFET devices ideal for ultra-low voltage applications.

3. Circuit Architecture

The circuit architecture of the proposed charge pump consists of two stages which are powered by energy harvested from radio-frequency systems. The harvested energy from RF systems is as low as 60 mV to 100 mV. The first stage includes clock generator circuit, buffer circuit, frequency divider and duty cycle generator circuit (Figure 3). The clock generator circuit essentially consists of odd number ofring oscillators to generate the necessary timing signals. The timing output obtained from clock generator circuit is a square wave and has a frequency of 1.6 MHz. The generated output pulse has unequal rise and fall times. In order to flatten the pulses, a buffer stage is provided. Next, the timing pulses are fed to a frequency divider circuit which consists of D flip-flops to generate appropriate frequency of 100 KHz. For getting optimum gain, the timing pulse is fed to a duty cycle generator to obtain a duty cycle of 75%.

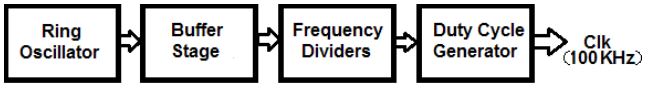

Figure 3. Timing circuit.

The second stage comprises CNFET based charge pump design which up-converts the input voltage as low as 100 mV to 1.05 V. Figure 4 presents the block diagram of a unit-stage charge pump design. It consists of ap-MOSFET pass transistor (P_1), n-MOSFET and p-MOSFET transistors (IN_1, IP_1), output capacitor (C_1) and Clk and Clkbar clock signals of frequency 100 KHz generated from previous stage. When Clk signal is high, transistors P_1 and IN_1 are ON and transistor IP_1 is OFF. The output capacitor C_1 is charged towards V_{DD}. When Clk signal is low, transistors P_1 and IN_1 are OFF, transistor IP_1 is ON and the output voltage across the capacitor C_1 is twice the supply voltage ($V_{out} = 2\ V_{DD}$). In order to boost the output voltage, Figure 5 displays the presented 10-stage charge pump design. During stage 1, when Clk signal is at V_{DD} and Clkbar signal is zero, the pass transistor P_1 conducts and the charge is transferred from V_{DD} to node 1. At stage 2, when Clk signal is zero, voltage at node 2 becomes 3 V_{DD}. Similarly at the end of 10^{th} stage, the output voltage (V_{out}) obtained across the final capacitor C_{10} is approximately ten folds of the supply voltage V_{DD}i.e $V_{out} \approx 10\ V_{DD}$.

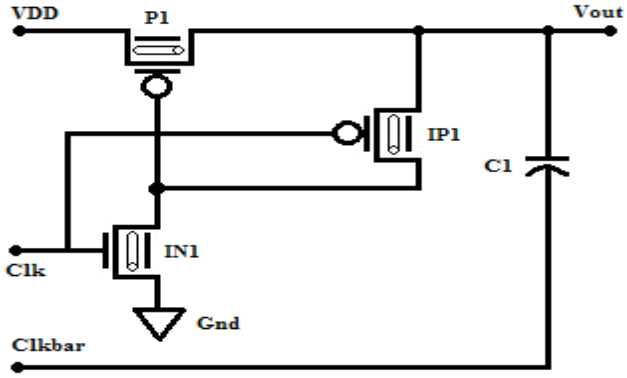

Figure 4. Block diagram of the unit-stage charge pump.

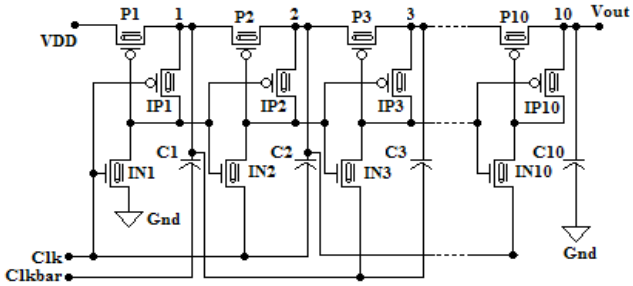

Figure 5. Block diagram of the proposed charge pump.

4. Results and Discussion

The charge pump circuit being proposed here has been realized with CNFET and evaluated using 32-nm CNFET model at DC voltage ~ 100 mV. The circuit operates in the input domain of 80-100 mV, which is boosted up to ≈1.05 V, with the conversion-ratio (M) greater than 10. The output of clock signal with 75% duty cycle is shown in Figure 6. The change in value of output voltage (V_{OUT}) with reference to time (t) is presented in Figure 7. As shown in Figure, the circuit achieves 1.05 V DC output voltage when 100 mV input is applied.

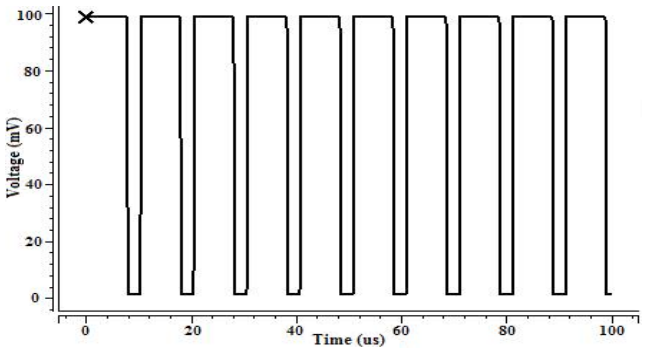

Figure 6. Output of timing stage.

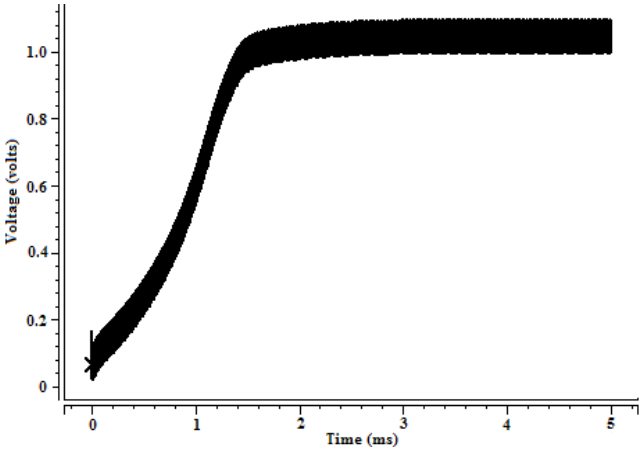

Figure 7. Output voltage versus time.

The result presented in this work is based on extensive simulation on SPICE using experimentally validated CNFET model of Stanford University[12].

5. Conclusion

This work demonstrates a low voltage charge pump convenient for voltage up-conversion from low power ambient sources. The charge pump operates with an input voltage as small as 100 mV and achieves an output voltage as high as ~1.05 V. The proposed circuit uses carbon nanotube transistors with extremely low device threshold (V_T) variations.

6. References

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