Low-threshold CMOS Rectifier Design for Energy Harvesting in Biomedical Sensors

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ABSTRACT

The power transfer efficiency of energy harvesting systems is strongly dependent on the power conditioning circuits, especially rectifiers. The voltage drop across rectifier and its leakage current can drastically influence the efficiency. The hybrid energy harvesters impose even more severe constraints on the rectifier. The low V_{th} transistors and bulk regulation technique are used in this work to mitigated the voltage drop and leakage current, respectively. It has been shown that the bulk regulation stops the current leakage through body of PMOS transistor. A near zero threshold cross connected CMOS rectifier is presented in this work using the standard 180nm UMC technology and experimental analysis are carried out to evaluate the circuit performance.

Keywords

Hybrid energy harvesting, CMOS rectifier

1. INTRODUCTION

The increasing demand for biomedical implants is triggered by numerous factors such as reducing healthcare costs, enhancing quality of human life, and understanding human anatomy and physiology [8]. Supplying the electrical power to implants, regardless of their function and specifications, is the most stringent constraint to implant functionality. The research on energy harvesting systems is targeted significantly to find autonomous energy supplies as an alternative to batteries in low power electronic devices such as wireless sensor networks and biomedical implants. Energy harvesting systems are categorized based on the transduction mechanisms into inertial mass vibrations, near/far field wireless transmission, photo-voltaic cells, etc. The efficiency of energy harvesters generally depends on transducer as well as its following power conditioning circuit. The transducer part is application dependent and its optimization depends on a very wide set of parameters such as inductive or mechanical couplings. However, power conditioning components are all in electrical domain that consist of resonance circuit, rectifier, regulator and converter [6]. Regardless of transduction mechanism the output electrical energy is in the form of alternating current or voltage. Rectifiers are needed to generate useful direct current (DC) supply for electronic circuits. Therefore rectifiers are the most essential part of power conditioning in energy harvesters. The development of hybrid structures that can combine distinctive attributes of individual energy harvesting techniques at the same time is the recent challenge in the design of high efficiency energy harvesters [3,5]. For example, piezoelectric harvesters have a higher efficiency at high frequencies, while

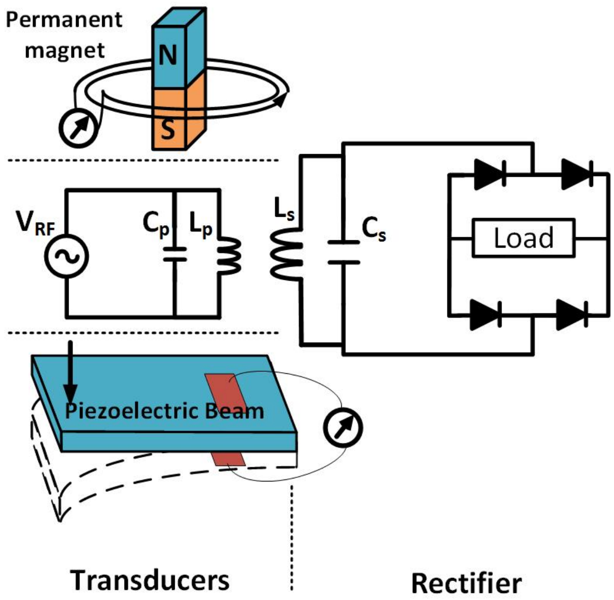

Figure 1: Hybrid energy harvesting system.

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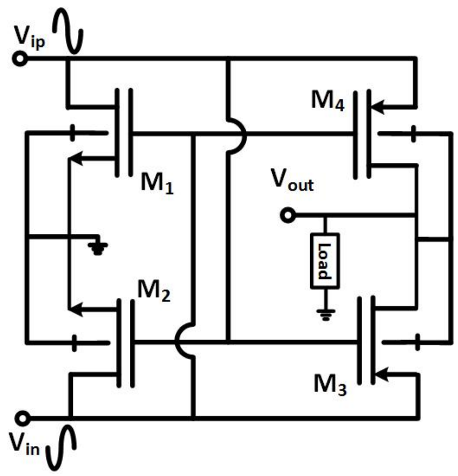

Figure 2: Differential drive (Cross-connected) CMOS rectifier

electromagnetic induction generates higher energy levels at low frequencies. Therefore combining these two techniques can lead to a broad band energy harvester. In addition, the radio frequency (RF) energy harvesters are implemented by electrical components only without any mechanical interaction, which gives a higher reliability compared with inertial counterparts. Though the inertial energy harvesters can generate higher output power compared with the RF counterparts. Therefore, in a hybrid system the RF energy scavengers could be used as a backup solution. A hybrid piezoelectric-RF energy harvester is presented in [5], where the piezoelectric output voltage is used to bias the rectifier up to the conduction point, in order to facilitate a more efficient conversion for weak RF inputs.

In this work the rectifier specification due to each energy harvesting technique is discussed and a highly efficient rectifier is implemented in CMOS. The conditions imposed on rectifier by each energy harvesting technique are discussed in Section 2. Section 3 introduces the proposed rectifier and experimental results are presented in Section 4.

2. CMOS BRIDGE RECTIFIERS

In conventional rectifier applications, Schottky diodes offer a superior performance. Their lower threshold voltage and reverse leakage results in higher conversion efficiency. However, it is impossible to implement Schottky diodes in standard CMOS processes. Popularity of CMOS rectifiers is due to their integration capability with the other electronics including sensor readout circuits, transceivers, etc. Diode connected CMOS transistor can be used as rectifier elements with minimum $1V_{th}$ voltage drop. This translates to $2V_{th}$ in a full bridge rectifier, which is more than the typical peak voltage induced in the secondary coil/antenna of RF energy harvesters. In an improved bridge rectifier for low frequency applications, i.e. inertial energy harvesters, transistors are employed in switch configuration instead of diode-connected as illustrated in Figure 2 [1]. The minimum input voltage is reduced to $1V_{th}$ that saves significant power in micro-energy harvesting. This circuit is also used for RF energy harvesting as differential drive CMOS rectifier [2] or

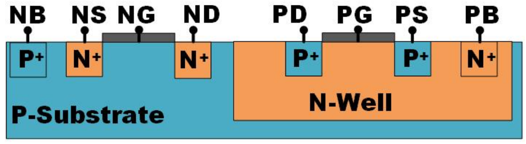

Figure 3: Cross section of standard CMOS transistor.

complementary CMOS switch rectifier [7].

Zero-threshold NMOS transistors are used in [9] to implement a voltage rectifier-doubler. In CMOS fabrication technology in order to make adjacent complementary transistors an n-well/p-well structure is needed as illustrated in Figure 3, which avoids zero-threshold p-n junction. Therefore, only one type of zero-V_{th} transistors (NMOS) is available in CMOS technology. Though, both types are needed to implement the differentially driven bridge rectifier in Figure 2. A silicon-on-saphire (SOS) fabrication technology is used in [7] to implement complementary near-zero-V_{th} transistors. However, non-standard processes result in extra fabrication costs.

3. BULK-REGULATED LOW-THRESHOLD (V_{TH}) RECTIFIER

As mentioned earlier in Section 1 hybrid energy harvesters are highly desirable for efficiency and reliability enhancement. However, hybrid transduction imposes different constraints on rectifier circuits. Several researches have been contributed in recent years to improve the efficiency of rectifiers. Though, the reported figure-of-merits fail to thoroughly describe the rectifier performance for hybrid applications. For example, the efficiency can be influenced by either reverse leakage due to high voltage outputs from piezoelectric transducers, or low voltage outputs from electromagnetic transducers that are unable to overcome the rectifier potential barrier. In addition, the high frequency outputs from RF transmitter might not be efficient due to the rectifier frequency response. In most of the researches carried out on the differentially driven CMOS rectifier, leakage currents are assumed to be ignorable. However, simulation results show that in high voltage regime, it can be even larger than the load current. In order to stop leakage current a bulk regulation technique is employed here, as shown in Figure 4.

Low-V_{th} devices are used in this design, in order to strike a compromise between the normal and zero-V_{th} transistors. Low-V_{th} CMOS transistors are available in standard fabrication technologies by low doping levels in well regions. The NMOS body (P-Substrate) in Figure 4, is connected to ground that avoids any leakage current through body. The PMOS body (N-well) should be connected to the most positive voltage of the circuit. Bulk regulation transistors (MB1-MB4) switch the body of PMOS transistors to the highest voltage, which can be either the output voltage or the input voltage. The simulation results for cross-connected rectifier with normal transistors and low-voltage transistors is compared with the bulk regulated rectifier circuit, as illustrated in Figure 8. In this simulation output load is a 10KΩ resistor in parallel with a 100nF capacitor. The negligible differ-

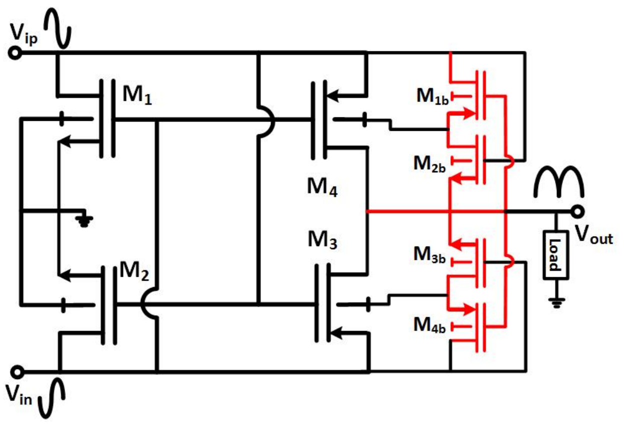

Figure 4: Bulk-regulated differential drive (Cross-connectd) CMOS rectifier

ence in the steady state load voltages is due to the different impedances seen from the rectifier inputs. The aspect ratios are the same for each transistor in corresponding circuits, though the difference is due to unequal impurity doping between normal and low-V_{th} transistor as well as added bulk regulation transistors. The bulk current of PMOS transistor M3 that is activated in the same input cycle in three different circuits is monitored in Figure 4. The bulk leakage current spikes in rectifier with normal transistor (M.b) and low-V_{th} transistor without bulk regulation (MLV.b) is much larger than load current ($\frac{Vout}{RL}$). However, the bulk leakage current in bulk-regulated circuit (MLVBR.b) is zero.

4. EXPERIMENTS

The proposed circuit is implemented in UMC 0.18 um CMOS technology and tested with different loads. The efficiency of the proposed circuit was shown in a previous work to be higher than Schottky diodes [4]. However adding the bulk regulation transistors influence the large signal frequency response of the circuit. The large signal frequency response of the rectifier is measured by applying sinusoidal inputs and varying the frequency. As illustrated in Figure 7, the power transfer after a certain frequency (1MH in this case) drops down significantly. This is mainly due to the wide aspect

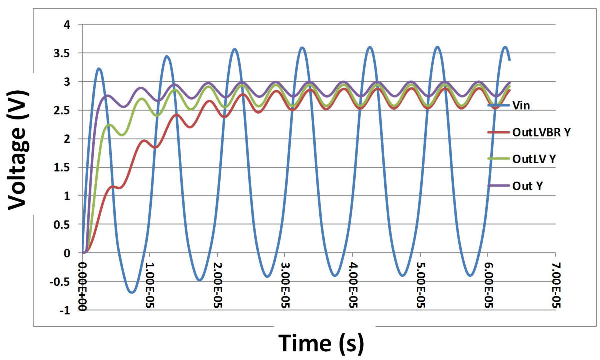

Figure 5: Transient and steady-state load voltage of CMOS rectifiers with normal and low-V_{th} transistor with and without bulk regulation.

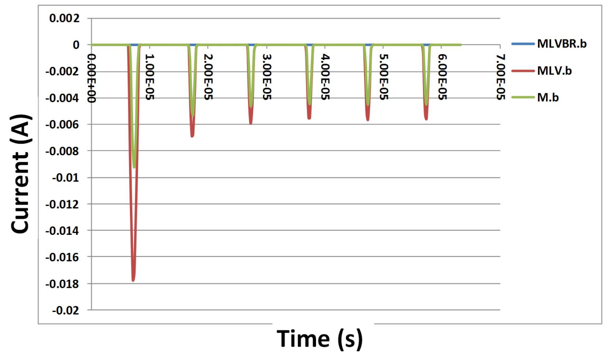

Figure 6: Transient and steady-state bulk current of CMOS rectifiers with normal and low-V_{th} transistor with and without bulk regulation.

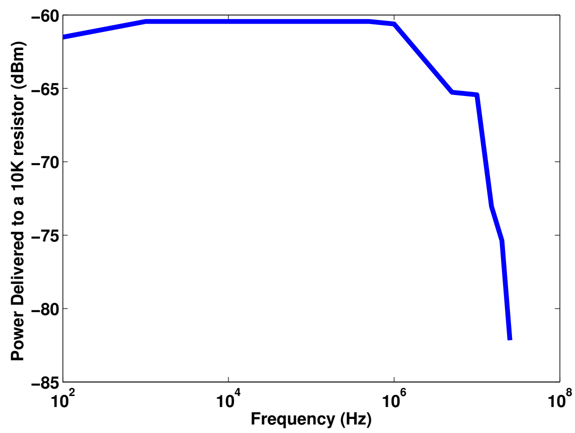

Figure 7: The large signal frequency response of CMOS rectifier

ratios of the transistors, which was selected to minimize the ohmic drop on the rectifier element.

The transfer characteristic of bulk-regulated rectifier for several load resistors is measured using X-Y mode of oscilloscope. As illustrated in Figure 8, the slope of the curve in conduction region varies with the load. The minimum voltage required to turn on the rectifier is also dependent on the load resistor.

5. CONCLUSION

The hybrid energy harvesting can boost the efficiency and reliability of autonomous sensors in applications such as biomedical implants. However, hybrid transduction mechanisms impose stringent constraints on the power conditioning circuits especially the rectifier. A CMOS rectifier with bulk regulation is designed using low-V_{th} transistors to mitigate leakage currents and voltage drop across the rectifier. The proposed circuit is implemented in 0.18um UMC CMOS technology and successfully characterized.

6. ACKNOWLEDGMENT

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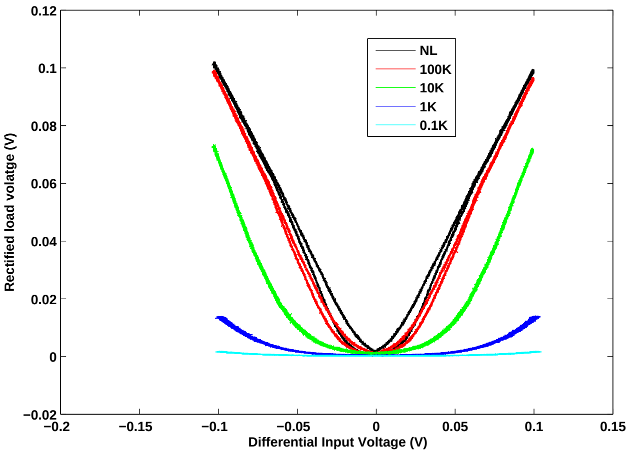

Figure 8: The rectifier input-output transfer characteristic for several ohmic loads.

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