A Highly Efficient 0.18um CMOS Rectifier For Vibrational Energy Harvesting System in Embedded Electronics Design

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Abstract

The energy harvesting research falls into two key areas. One is developing optimal structures of energy harvesting, and the other is designing electronic circuits that are efficient enough to store the generated charge. Optimization of microelectronic devices to reduce energy consumption, while all devices strive to achieve excellent efficiency, balancing performance and power consumption, the application area will dictate design constraints such as size, energy budget, and maximum power. Regarding the research area of optimal design of electronic circuits, two highly efficient CMOS rectifier for vibrational energy harvesting system is proposed. Based on design considerations, rectifier plays an important role in the application of an energy harvesting system and wireless power transfer system. So, The performance of the rectifier decides the efficiency of the system. Two proposed designs of low voltage Rectifier are Suggested for operating frequency of 13.56 MHz. The first design using the two-stage structure and an Improved precision active diode and the second design using diode voltage booster The suggested structures are established using a standard 0.18um CMOS process can perform the minimum operating voltage is lower than previously published paper. The rectifier can work at a wide range of input voltage amplitudes of 0.45V up to 1.95V and the second design to 1.98V. So, the proposed rectifiers are suitable to work in Different Types of vibrational energy harvesting system, Electrostatic Energy harvester, Electromagnetic Energy Harvester, Piezoelectric Energy Harvester. The proposed rectifiers can achieve peak voltage conversion efficiency of over 82% and power efficiency over 89%. Simulated power consumption of the rectifier is 0.23uW, which is about 26% smaller than the recently published results.

Keywords__*Low Voltage Rectifier, Improved Precision Active Diode, Low power design, Embedded Electronics, Energy Harvesting, CMOS Circuits, Battery-less Technology, mechanical vibration, wearable and embedded sensors, Low power circuits and architectures, energy efficiency, Diode Voltage Booster. Wireless Power Transfer WPT*

I. INTRODUCTION

The energy and power issue for Embedded systems is the "capability of performing work." Power, being equal to the work divided by the time that it takes to do it, indicates how fast this work is done for a certain amount of energy or how much energy is consumed to achieve a task, e.g., a computational operation (in a specified time interval). The power required to operate current Embedded systems ranges from the mW level for small autonomous sensor systems to tens of M.W.s for HPC systems. In between these power, levels lie a large number of devices, including embedded sensors, mobile phones, smartphones, tablets, personal computers, servers, and cloud computing storage systems. The continuous scaling of silicon chips has driven the use of Embedded systems. The original drivers for scaling came from improving the performance of computers, but as the size of transistors was reduced, so was the power consumption enabling many portable systems to be developed. The advantage of using mechanical vibrations to harvest energy is that they are the most common energy source available in many environments. Fig. 1 shows the Schematic of vibrational energy harvesting system design [1]

II. System Design of Vibrational Energy Harvesting :

The energy harvesting research falls into two key areas. One is developing optimal structures of energy harvesting, and the other is designing electronic circuits that are efficient enough to store the generated charge. Fig.1 shows the Schematic of vibrational energy harvesting system design. Regarding the research area of optimal design of electronic circuits, A highly efficient CMOS rectifier for vibrational energy harvesting system is proposed.

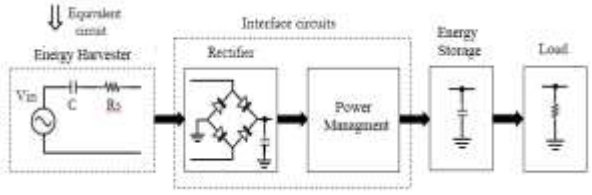


Fig.1. Schematic of vibrational energy harvesting system design

A. Importance of Rectifier in Energy Harvesting System :

The Rectifier performance is very important in the whole system design due to several reasons [2]:

a. Working frequency :

The working frequency should not be too low, considering the coil's size in the receiver if it is utilized in the biomedical implant devices. However, it should also not be too high for avoiding potential hazards to human safety. Based on these considerations, rectifier plays an important role in the application of the energy harvesting system and a wireless power transfer system. So, The performance of the rectifier decides the efficiency of the system [3].

b. Voltage efficiency :

The rectifier converts A.C. voltage supplied by the receiver to D.C. voltage and power delivered to circuit load. The voltage efficiency of rectifier decides output voltage. Higher efficiency means a larger output voltage.

c. Minimum operation voltage :

The rectifier used in the application must be self-biased. The energy received from the receiver is not only rectified signal. The peak amplitude of the input source also influences the output voltage. Inductive coupling between coils or capacitive coupling is the two leading technologies for near field applications. The distance between two loops and the relative position of the coil center influence the transfer efficiency. Thus, low voltage rectifier can cover the influence caused by the inductive coupling coils mismatch.

d. Power efficiency :

The wireless power transmission system consists of power amplifier, inductive coil, rectifier and regulator. It is essential to mention that the effectiveness of the rectifier is usually the bottleneck. Higher power efficiency means higher total efficiency;

B. The Active Diode Rectifier Circuit :

It is also known as Active-diode, is a configuration obtained with an operational amplifier to have a circuit behave like an ideal diode and rectifier. It is very useful for high-precision signal processing. With the help of precision rectifier, the high-precision signal processing can be done very easily [4].

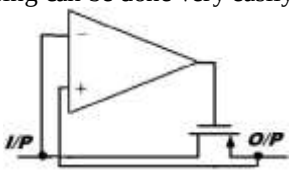


Fig.2 The Schematic of active diode [4]

To improve the voltage conversion efficiency and power efficiency, a concept of the active diode was first proposed in [4] instead of the connected diode transistors in the conventional passive rectifiers. The active diode works as an ideal diode without voltage drop and reverses current. Fig.2 shows the Schematic of active diode [4]. It is composed of a comparator and a transistor switch. It should be mentioned that the comparator should be powered by the output signal. When the input source amplitude is larger than the amplitude of output voltage, the comparator will turn on the switch and current flows from the input source to the output terminal and charges the load. When voltage amplitude of the output is larger than the input source, the comparator should turn off the switch immediately, otherwise reverse current will flow from output terminal to input terminal. The reverse current will decrease the power efficiency and increase the output voltage ripple. Thus, the design of active diode is very important. After the proposing of the active diode, the research of rectifier using active diode is promoted in many applications. Vibrational energy harvesting is one of the applications. Commonly, the voltage amplitude is very small. The proposed rectifier is composed of two stages: the negative voltage convertor and the active diode. Because the active diode comparator circuit, your input is power supply comparator and a significant problem this Circuit has two different Vth transistors used to correct all of the technology we use a voltage Vth. Input voltage range comparator (Common-Mode Input Voltage Range) equals VDD and could be used from the input for power supply the comparator circuit. Equ (1) represents the input voltage range. For this as Equation equal to VDD, must the input transistors are is a high Vth.

$$V_{tmax} = V_{DD} - V_{GS}(MP1) + V_{th}(MN1) = V_{DD}$$

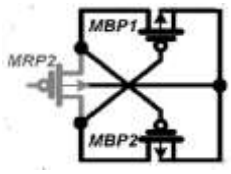


Fig.3 Dynamic bulk biasing technique with P-type bodyguard transistors for PMOS transistor

With connecting PMOS transistors' bodies to the highest reachable voltage, by using of two P-type guard transistors and connecting NMOS transistors' bodies to the lowest voltage with two N-type guard transistors, it could extremely block substrate current leakage and latch-up [5]. The process is in this way that the drain and source voltage are alternatively change to low and high, and the transistor body needs to be connected to the highest energy, this operation is occurred by cross-connecting. Active body biasing method with PMOS guard transistors (MBP1 and MBP2) for PMOS transistor (MRP2) is shown in Fig. 5.

An alternative version is given in Fig.3. In this case, when the input is more significant than zero, D1 is off, and D2 is on, so the output is zero because the other end of R2 is connected to the virtual ground and there is no current through R2. When the input is less than

zero, D1 is on, and D2 is off, so the output is like the input with an amplification. This Circuit has the benefit that the op-amp never goes into saturation, but its output must change by two diode voltage drops about 1.2V each time the input signal crosses zero. Hence, the slew rate of the operational amplifier and its frequency response (Gain–B.W. product) will limit high-frequency performance, especially for low signal levels. However, an error of less than 1% at 100kHz is possible.

C. The Improved Circuit of Low Voltage Active diode :

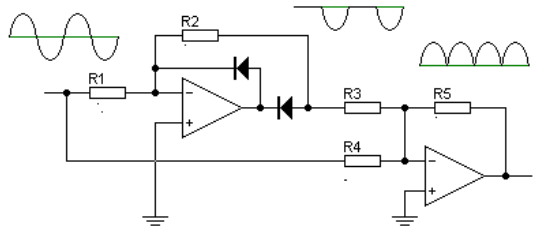


Fig. 3 The Improved Circuit of Low-Voltage Active Diode

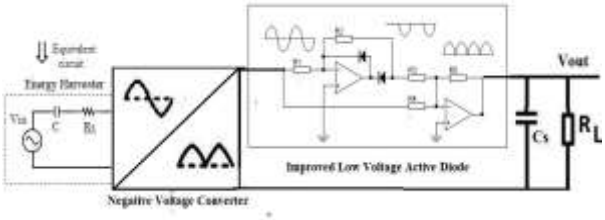


Fig.4 Schematic of the Proposed Improved Rectifier with Low-Voltage Active Diode

III. *A. Input Range and Voltage Conversion Efficiency :*

The proposed rectifier shown in Fig.4, can work at a wide range of input voltage amplitudes of 0.45V up to 1.95V, which is decided by the threshold voltage and breakdown voltage respectively of the standard 0.18um CMOS process. Breakdown voltage verification using cadence Tools is shown in Fig.5 This wide range of input voltages allows the rectifier to work in different types of vibrational energy harvesting system. The voltage efficiency y_v is defined as the fraction of the output D.C. voltage Vout and the input voltage amplitude |Vin|, which is shown in Eq. (1). The output voltage efficiency of the rectifier is higher with larger load resistors due to its high output voltage drop.

$$\eta_v = Vout / |Vin| = 100\% \qquad (2)$$

B. Power Efficiency of the Rectifier is calculated by:

$$\eta_P = \frac{\int_{t_1}^{t_1+T} v_{out}(t) \cdot i_{out}(t)\, dt}{\int_{t_1}^{t_1+T} v_{in}(t) \cdot i_{in}(t)\, dt} 100\% \qquad (3)$$

Where T is one period of the input signal, and t_1 is the start time. With increasing R_Load , the efficiency decreases, because the current through the ohmic load decreases and tends to the current through the comparator. The load capacitor is adapted for the applied frequency, so a capacitance of 10uF and a load of 50KΩ are used. The voltage efficiency for the lower frequency is better than 1kHz case. Since higher frequency will result in the delay of the comparator and increasing reverse current. However, at typical energy harvesting frequencies, the working frequency range of this rectifier is sufficient for most applications. The power consumption of the rectifier is simulated. The results show that the power consumption at 0.45V is 0.23 uW, which is about 26% smaller than the best recently published result.

IV. The Second Proposed Low Voltage Rectifier using Diode Voltage Booster :

With the need for increasing the power conversion efficiency, several Wireless Power Transfer WPT systems operating at the MHz frequency range as in the schematic diagram of a traditional WPT module is illustrated in Fig. 5 [10].

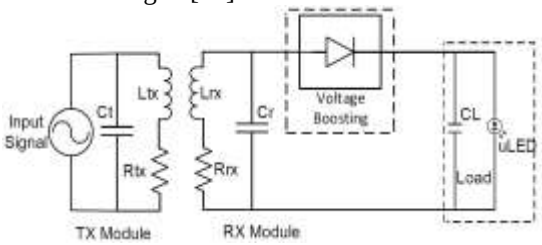


Fig.5.Schematic diagram of a conventional wireless power transfer system.

A rectifier is designed to maximize the power conversion efficiency focusing on input voltages less than 200 mV. This rectifier utilizes Schottky diodes to convert the input A.C. signal to a D.C. voltage. Schottky diodes have been used to operate in a wide range of frequencies [11]. To obtain high output voltage and high efficiency, Schottky diodes having a lower forward voltage drop than p-n junction diode, are used in the rectifier circuitry [12].

The design of an optimized CMOS rectifier circuits having good sensitivity and an acceptable efficiency has become the most important design issue in supply generation of WSNs and RFIDs. The previous research on the analysis and efficiency enhancement of CMOS rectifiers can be divided into four categories:

(a) Presenting mathematical model that matches the fabrication technology of CMOS rectifiers so that the resulting understandings from the model can be used for the design of efficient harvester system [15–17];

(b) Introducing different circuit techniques to optimize the performance of the conventional CMOS rectifier proposed in [18], which is usually considered as the main core of CMOS rectifier circuits; for example,[19] uses the Schottky diodes in the rectifier circuit to

achieve a low threshold voltage, while [20] uses native CMOS transistors with zero *V*th to increase the sensitivity of total rectifiers; the drawback of these methods is that they require a special process to create the Schottky diodes or native low *V*th transistors, which raises the cost of chip fabrication because the standard CMOS fabrication technologies do not implement Schottky diodes or native CMOS transistors; [21]introduces an internally *V*th cancellation (IVC) technique using the generated output voltage to enhance the input impedance of the rectifier circuit for connection to the matching network and compensation of the threshold voltage of diodes; [22] uses an auxiliary battery along with a battery voltage distributor in order to compensate for the threshold voltage in semi-passive applications; meanwhile, [22] uses an auxiliary rectifier chain to compensate for the threshold voltage of the rectifier; all of these mentioned techniques have been useful and could enhance the performance of conventional rectifier circuits;

(c) Introducing CMOS rectifier structures as the cross-coupled structure in [23] or the proposed self *V*th cancellation (SVC) technique in [23, 24]; these structures could also make reasonable improvements in rectifier circuit fabrication and enhance the performance of conventional rectifier circuits; it is noteworthy that a large number of today's researches are developing these structures;

(d) introduction of structures that include several transistors (e.g., 3 to 15 transistors) as a diode with close to ideal I-V characteristic; using these structures in half-wave and full-wave rectifiers, the performance of the rectifier circuit will be improved due to the enhanced I-V characteristic [25, 26].

In designing the optimized CMOS rectifier, it is very important to consider the structure of the diode used in the rectifier and its characteristics. In other words, the threshold voltage and the forward bias current of the diode are the determinants in the rectifier's performance as well as its leakage current in reverse bias region, which play critical roles in the performance of the rectifier circuit. All previous research works had tried to design a circuit with a decreased threshold voltage and leakage current and increased forward bias current for the rectifying diodes [26]

A. The Diode Connected NMOS or PMOS Structure :

The diode-connected NMOS or PMOS transistor is the most important part of a rectifier circuit. Therefore, analyzing the I-V characteristic of a diode-connected transistor helps to truly understand its operation in different regions. Before proposing the diode model, it is better to review conventional diode-connected transistor's connection schematic, its I-V curves, body effect of the transistor on its leakage current, and threshold voltage. Fig.6(a) shows the typical connection of a MOS transistor as a diode. As shown in Fig.6(b), the IV curve can be divided into 4 regions, namely, breakdown, reverse, sub-threshold, and forward [27]. In a MOS transistor, in which its bulk is not connected to its source, the body effect can affect the threshold voltage according to the body effect can affect the threshold voltage according to :

$$V\text{th} = V\text{tho} + k1\,(\sqrt{\varphi s} + V\text{SB} - \sqrt{\varphi s}) + k2V\text{SB} \qquad (4)$$

where $k1$ and $k2$ are the parameters which depend on channel doping. *V*th is the threshold voltage of transistors, *V*tho is the intrinsic threshold voltage of the transistor, *V*SB is the source to the bulk voltage of the transistor, and φs depends on CMOS technology.

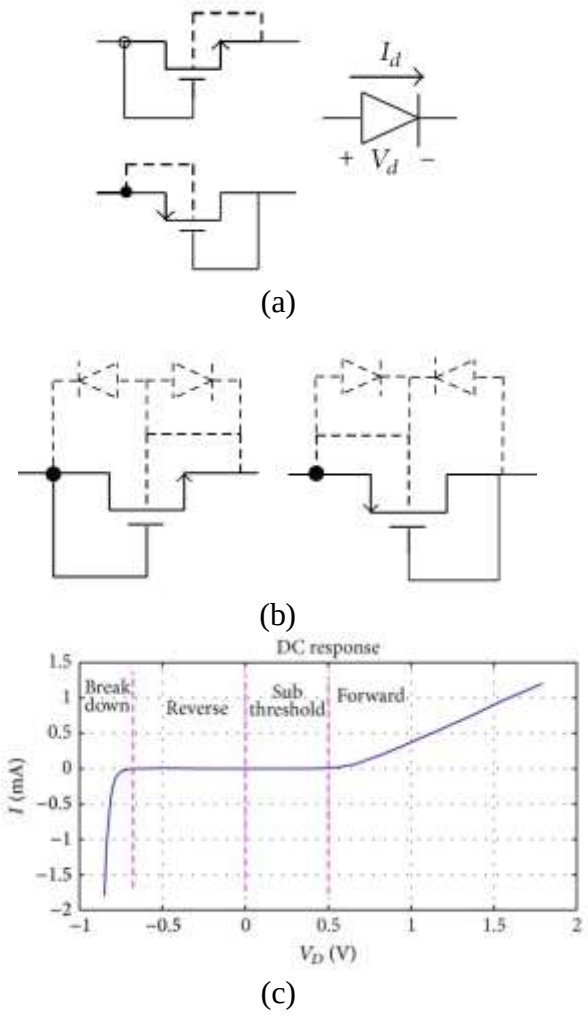
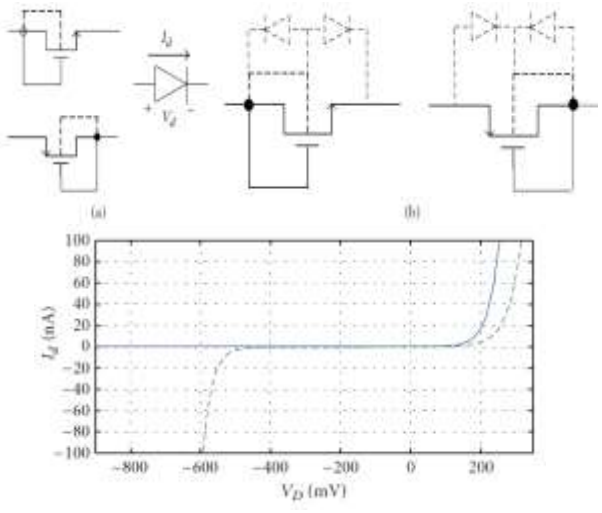


Fig.6. (a) A conventional diode-connected MOS transistor, (b) the intrinsic P.N. junction of the MOS transistor, and (c) *I-V* characteristic for 0.18 μm standard NMOS transistor. TSMC process, and W/L=2μm/0.18μm

A desirable specification can be defined for an ideal diode in CMOS rectifiers as follows: a proper diode for CMOS rectifier needs a low threshold voltage as well as a shallow leakage current in the reverse region. So, a desirable structure for the diode (diode-connected transistor) is shown in Fig. 7(a). As shown in this figure, its bulk is connected to the drain instead

of the source. Of course, there is no difference between the source and drain in CMOS technology, but we propose here that it means that the bulk is connected to the port of the transistor that plays the role of the drain in Circuit and is shorted to the gate in diode connection. According to (1), when the proposed diode is biased in the forward region, the source bulk voltage of the transistor is negative. In this region, it decreases the threshold voltage of the diode in comparison to the conventional diode-connected MOS transistors. This analysis is presented for NMOS diode-connected transistor and could be extended for PMOS by reversing the voltages. On the other hand, when the proposed diode is biased in the reverse region, the source-bulk voltage is positive, and this leads to a reduction in the reverse current of the diode in comparison to conventional ones. Fig.7(b) shows the intrinsic P.N. junctions between the bulk and the drain/source of the MOS transistors. As shown in this figure, the intrinsic P.N. diode in forwarding bias improves the current of the diode as compared to the conventional diode in Figure 1(c), in which the P.N. diode is reverse biased in the forward region. Conversely, the P.N. diodes as displayed in Fig.7(b) are off in the reverse bias region despite the P.N. junctions of the conventional diode which are forward biased in this region. So the proposed connection for the bulk of the transistors can improve the performance of the diode-connected MOS transistor for CMOS rectifier design. Fig. 7(c) shows the current versus voltage curve of the proposed diode-connected transistor in comparison to the conventional diode. As shown in Fig. 7(c), in the same VD of 0.316V, the conventional diode-connected transistor's current is 153.2 nA, and the proposed one's current is 997.2 nA. It means 6.2x improvement in diode-connected performance. For another example, in point of VD = 0.905V, the conventional diode-connected transistor's current is 0.275mA, and the other one's current is 6.43 mA. This means 23.38x improvement[27] .



(c)

Fig. 7. Specifications of 0.18 μm TSMC process and W/L = 2 μm/0.18 μm for the standard NMOS transistor. (a) The diode-connected MOS transistor, (b) the intrinsic P.N. junctions of the MOS transistor, and (c) I-V characteristic to show the difference between forwarding current and reverse (leakage) current of proposed and conventional diode-connected transistor [27].

In summary, the diode-connected MOS transistor is used to improve the diode's I-V characteristics in CMOS rectifiers. This diode has better performance in both forward and reverse regions of its operation. It utilizes the intrinsic bulk-source and bulk-drain P.N. junctions in the desired direction to reduce the leakage current and threshold voltage. A one-stage conventional rectifier using the diode-connected is analyzed and compared with the same rectifier using the conventional diodes. Furthermore, an optimization method for maximum efficiency is applied for the design of an optimum CMOS rectifier. The rectifier is designed in TSMC 0.18μm CMOS technology without any additional masks using Cadence Tools.

B. The Second Proposed Rectifier Design using diode-connected Voltage Booster :

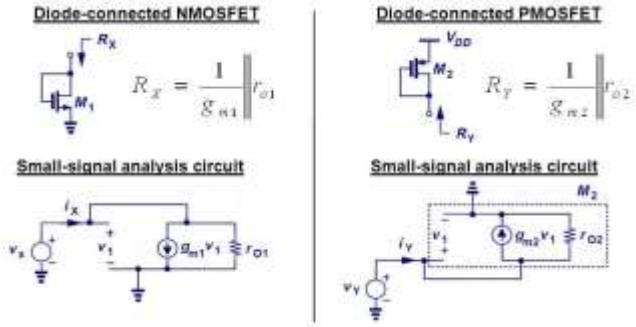


Fig. 8. Diode - Connected MOSFETs , the small-signal model of a PMOSFET is identical to that of an NMOSFET

In Fig.8 when the drain and gate of a MOSFET are connected the result is a two-terminal device known as a diode-connected transistor. VGD < Vt for Saturation region, since VGD is zero, then the method is always in the saturation region. the small-signal model of a PMOSFET is identical to that of an NMOSFET

Optimal design of a voltage boosting rectifier for wireless power transfer of Energy Harvesting system is proposed. **The second proposed** configuration using diode-connected MOSFET voltage-booster to extend the input voltage by avoiding the breakdown of the gate oxide. To further broaden the voltage booster idea, One can use the resistive-diode energy-boosting, as shown in Fig. 9. So that the positive swing of G2 can be made larger than the negative swing. The positive voltage swing around the supply voltage is larger than the negative swing. In this case, the Circuit in Fig. 9a is more convenient, where M1 and M2 have the same voltage swing at the gate-drain. As a result, the Circuit works under output power without causing performance degradation. By choosing the value of Rd and the size of the diode-connected transistor M3, one

can specify the threshold voltage at which the Rd-M3 starts conducting and boosting the positive swing at G2. This extra path enables G2 to follow the rise in D2 with a smaller attenuation than the fall in D2. During this transient response, the average charge stored on Cb increases, causing Rd-M3 to conduct for a smaller percentage of the duty cycle. The average voltage at G2 increases up to the point where Rd-M3 no longer conducts. In steady-state, the Rd-M3 path is off, and the positive and negative swings at G2 are equal. Fig. 9b shows the drain and gate voltages of transistor M2 versus time for different values of Rd. The voltage swing at D2 is not affected by Rd, and the peak-to-peak swing of VG2 depends on Rd-Cb and not Rb. However, as the value of Rd is reduced, the average voltage of VG2 increases.

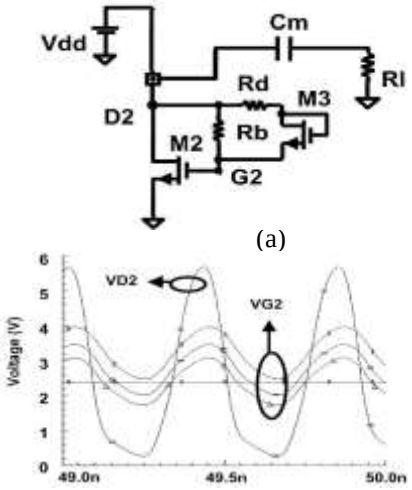


Fig. 9 (a) CMOS Diode voltage Booster (b) Voltage waveform, VG2 shown for three different values of Rd

In This Topology, the voltage swing can be about three times the supply voltage (with a larger positive swing than negative around the supply voltage). In this situation, the boot-strapped cascade configuration can be used to have the same maximum voltage swings at gate-drain of M1 and M2. Therefore, a more abundant supply voltage can be applied, resulting in higher output power.

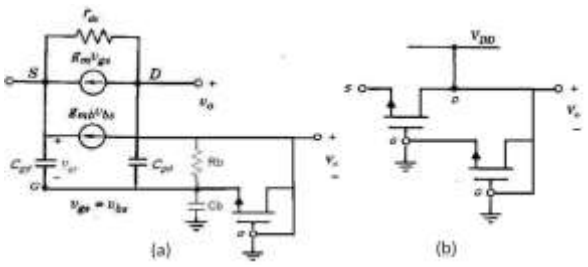


Fig. 10a Equivalent circuit of diode connection to the gate to boost the gate-bias voltage

Fig. 10b Indicates that the gate voltage follows the same variation of drain-voltage, so the voltage difference is constant and less than the breakdown voltage. This is a great chance to use a higher supply voltage to target higher output power.

V. Simulation Results and Performance Comparisons

The performance comparisons of the first proposed design with other previously reported rectifiers. The lowest operation voltage of previous rectifiers is 0.5V in [5] with a 500mV low threshold voltage 0.35um CMOS process. However, it cannot work when the input voltage is larger than 1V, which blocks the application field. The rectifier proposed in this paper overcomes these drawbacks. It can not only work at a 0.45V input voltage but also operate at a wide range input voltage amplitudes of 0.45V up to 1.95V compared with 0.5V to 1V in [6] and 0.28V to 0.7V in [7-8] In this paper, a wide range input voltage amplitude and highly efficient rectifier for energy harvesting system was proposed. The rectifier is well suited for an input amplitude as low as 0.45V and can work at a wide range of input voltage amplitudes of 0.45V up to 1.95V under a standard 0.18um CMOS process. The proposed rectifier can achieve peak voltage conversion efficiency of over 82% and power efficiency over 89%. Simulated power consumption of the rectifier is 0.23uW at 0.45V, which is about 26% smaller than the best recently published results.

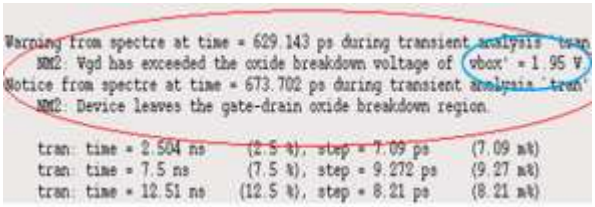


Fig. 11 **Simulation Results** of Breakdown voltage verification of standard 0.18 um CMOS process

Table 1. Performance Parameters Comparisons between Low Voltage Rectifiers

Performance Parameters	IEEE [8]	IEEE TCAS [9]	**Our First Design Improved Active** Diode	**Our Second Design Diode Voltage Booster**
Technology	0.35um CMOS	0.18um CMOS	0.18um CMOS	0.18um CMOS
Input Voltage Amp.	0.28V-0.7V	0.5V-1V	0.45V - 1.95V	0.45V - 2.1V
Voltage Efficiency	76%-97% (R_{Load}=40k	90% (R_{Load}=50k)	82% (R_L=50k)	88% (R_L=50k)
Power Efficiency	78%-95%	up to 95%	up to 89%	up to 92%
Working Frequency	10Hz-3KH	10Hz-10KHz	13.56 MHz	13.56 MHz

VI. Conclusions

Regarding the designing of Embedded electronic circuits, the optimal Energy Harvesting design for 0.18um CMOS Circuits is achieved by two designs of Low Voltage Rectifier using improved precision active diode. The proposed rectifier is designed for 13.56 MHz using two-stage structure of improved precision active diode and diode voltage booster under a standard 0.18um CMOS process can perform the minimum operation voltage is lower than

previous published paper and the rectifier can work at a wide range of input voltage amplitudes of 0.45V up to 1.95V and 2.1V. This allows the proposed rectifier to work in Different Types of vibration energy harvesting system, Electrostatic Energy harvester, Electromagnetic Energy Harvester, piezoelectric Energy Harvester. The proposed rectifiers can achieve peak voltage conversion efficiency of over 82% and power efficiency over 89%. Simulated power consumption of the rectifier is 0.23 uW at 0.45V, which is about 26% smaller than the best recently published results.

VII. Future Work

The advantage of using mechanical vibrations to harvest energy is that they are the most prevalent energy source available in many environments. So to enrich the energy harvesting solutions using the mechanical vibrations sources, we suggest to use the self-biasing technique to solve the problem of using the cascode topology where the supply voltage is limited by the breakdown voltage of the common-gate transistor. So the self-bias technique is used at the common-gate to allow the input voltage swing at the gate to boost the biasing voltage above 2Vdd. Consequently, one can have a larger signal swing at the output before encountering the breakdown of CMOS devices.

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