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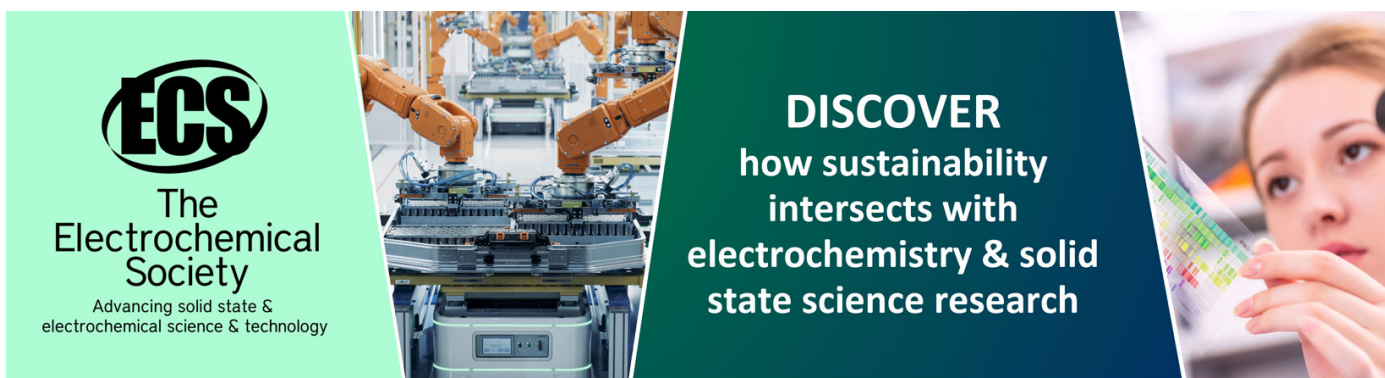
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An Integrated Circuit Design of High Efficiency Parallel-SSHI Rectifier for Piezoelectric Energy Harvesting

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Abstract. This paper presents the design and implementation of a rectifier for piezoelectric energy harvesting based on the parallel-synchronized-switch harvesting-on-inductor (P-SSHI) technique, also known as bias flip circuit[1]. The circuit is implemented with 0.25 μm CMOS high voltage process with only 0.9648 mm^2 chip area. Post-layout simulation of the circuit shows the circuit extracts 336% more power compared with the full-bridge rectifier. The system's average control power loss is 26 μW while operating with a self-made MEMS piezoelectric transducer with output current 25 μA 120Hz and internal capacitance 6.45nF. The output power is 43.42 μW under optimal load of 1.5 $\text{M}\Omega$.

1. Introduction

The concept of machine to machine(M2M) and internet of things(IOT) have drawn industry's much attention in recent years. In order to monitor different status of the environment, the requirement for wireless sensors and IOT devices is increasing. Due to the quick advancement of semiconductor fabrication technologies and ultra-low power integrated circuit design, the power consumption of wireless transceivers and microcontrollers were reduced to microwatts level. However, most wireless devices are still powered by batteries nowadays, and the reliability and performances of the device are limited by the use of batteries and battery lifetime. IoT devices and sensors in the future are better to be environmental friendly and maintenance free. By piezoelectric energy harvesting devices, we can transform vibration energy from the environment into electrical energy, thus solving the issue for powering IOT devices and sensors without using batteries.

Piezoelectric energy harvesting devices can potentially supply up to hundreds of μW of available power[2]. In order to use the harvested power, we need an interfacing circuit to transform the output energy from the transducer in AC (alternating current) form into stable DC (direct current) form required by the wireless transceivers and microcontrollers. Since the power consumed in the interface circuit reduces the amount of usable electrical power, the control of interface circuitry should be ultra-low power. In addition, the commonly used full-bridge rectifier limits the power extractable from piezoelectric devices. Rectifier structures other than full-bridge rectifier were researched and presented in order to extract more power. In this paper, we present a self-powered rectifier for piezoelectric energy harvesting based on the parallel-synchronized-switch harvesting-on-inductor (P-SSHI) technique, which was already proved to boost the output power of piezoelectric energy harvesters[3]. The



performance of the full bridge rectifier and the P-SSHI interfacing circuit, the architecture of proposed integrated circuit implementation, and the experiment and SPICE simulation result are all detailed as follows.

2. Discussion of Full-Bridge Rectifier Interface Circuit and P-SSHI Interface Circuit

This section briefly discusses the performance of the full-bridge rectifier and P-SSHI interfacing circuit. Fig.1 shows a full-bridge rectifier interface circuit, also known as a standard interface circuit. Current source S_1 along with C_0 is piezoelectric device's equivalent circuit in current form. We assume all components are ideal and diode has zero voltage drop for simplicity. From the analysis of Wu et al.[4], the maximum output power of standard interface charging a capacitor can be calculated by:

$$P_{\max} = \frac{I_p^2}{2\pi\omega C_0} * \frac{C_1}{C_1 + 2C_0}$$

,where I_p is the amplitude of output current of piezoelectric device, and ω is the operating frequency.

Figure1. Full-bridge rectifier interface circuit

The P-SSHI interface circuit is shown in Fig.2. The only difference between P-SSHI and standard interface is that P-SSHI has an inversion phase while the other one does not. Inversion phase occurs at peak voltage of piezoelectric device's output voltage, which is generated by closing S_1 for half of the L_1C_0 oscillation period. If the voltage before inversion is V_{before} , the voltage after inversion V_{after} can be expressed as,

$$V_{\text{after}} = -\gamma \cdot V_{\text{before}}$$

,where γ is the inversion factor, a function of circuit's quality factor. By the same analysis method for full-bridge rectifier interface circuit based on Wu et al.[4], the maximum output power of P-SSHI charging a capacitor can be expressed as,

$$P_{\max} = \frac{I_p^2}{2\pi\omega C_0} * \frac{C_1}{C_1 + 2C_0} * \frac{2}{(1 - \gamma)}$$

With a typical inversion factor of 0.7, the maximum output power of P-SSHI interface circuit can reach up to 667% of standard interface circuit without considering control and other power losses. Thus, we proposed a self-powered P-SSHI rectifier circuit for boosting output power of piezoelectric energy harvesters. The architecture and simulation results are explained in the following sections.

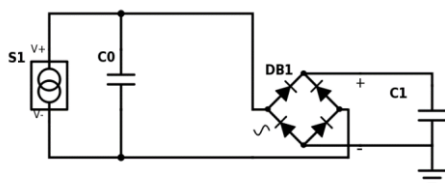


Figure1. Full-bridge rectifier interface circuit

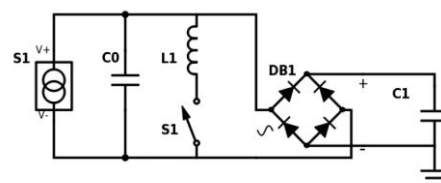


Figure2. P-SSHI rectifier interface circuit

3. Architecture of the Proposed SSHI Rectifier

Fig.3 shows a piezoelectric device's equivalent circuit along with the proposed circuit, which consists of a peak detector, a comparator for SSHI switching instance control and a full bridge rectifier. The output power of this circuit is stored in the capacitor C_r for later use.

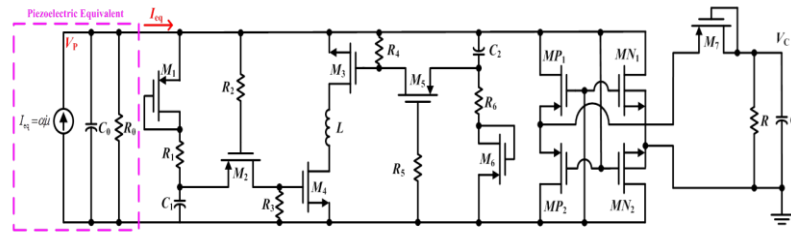


Figure3. Proposed SSHI rectifier circuit

The operation of the SSHI switching control and waveforms are shown in Fig.4. During the half cycle of the vibration, V_p will charge V_c up to $V_p - V_{th,M1}$, which is nearly the peak voltage of the piezoelectric transducer output. As V_p starts to fall, V_c will be held until V_p is smaller than $V_c - V_{th,M2}$. At this crossing point, transistor M_2 will be turn on, and thus turning on M_3 for a bias flip action. Resistor R_3 provides a current path for V_c to discharge. Diode D_1 is placed in series with the bias flip path to prevent over flipping, in the proposed design, the body diode of M_3 and M_4 in Fig.3 serves the function of the diode D_1 . The proposed control circuit is modified and redesigned from previous work of Lallart et al.[5]. In this work, in order to implement the circuit with CMOS (complementary metal oxide transistors) integrated circuit design, the original BJT (bi-polar junction transistors) are replaced with all MOSFET (metal oxide field-effect transistors) design to lower the overall losses in the circuit and also the power consumption of control circuit.

The range of operating frequency of the proposed circuit depends on the value of R_1 and C_1 . If the operating frequency is too high, the circuit will not be able to detect peak voltage of the piezoelectric waveform due to switching time delay caused by R_1C_1 time constant. In addition, the value of R_1 and C_1 has to be large enough to turn on the switch long enough for proper bias-flip action.

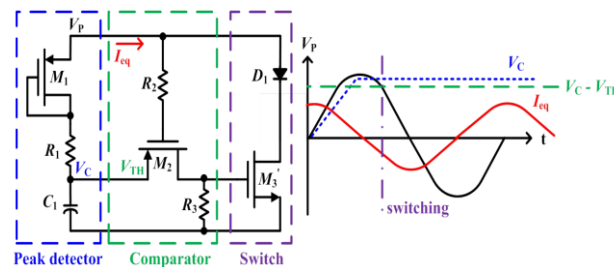


Figure4. Proposed SSHI rectifier circuit

4. Experiment and Simulation Results

A discrete components version of the proposed circuit was made, tested, and compared with standard interface and the circuit proposed by Lallart et al[5]. Since discrete components can handle larger power, though the loss in the circuit is also higher, the circuit was tested with a self-made piezoelectric transducer with higher output power. The output current of the transducer is $70 \mu\text{A}$ 120Hz, and the internal capacitance is 7 nF . The tested output power result is shown in Fig.5, which verified the feasibility of the proposed design.

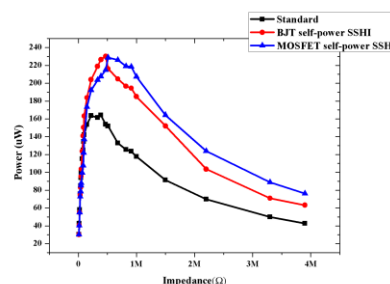


Figure5. Discrete version of self-powered P-SSHI output power verses output impedance

The circuit along with the model of our self-made MEMS piezoelectric transducer[2] is then simulated with Spice, the simulation result of output power verses output impedance is shown in Fig.6. The output current of our self-made transducer is 25 μ A 120Hz, and the internal capacitance is 6.45 nF. The result shows that the proposed system is functional and provides 336% more power than standard interface. A table of the performance and working condition of this chip is presented in Table 1, and the layout diagram is shown in Fig.7. Simulated result of this chip compared to state-of-the-art circuits is presented in Table 2. The circuit has been taped out and now in fabrication process, and the test chips will be returned in November for further testing results.

Table 1. Performance and working condition of the proposed circuit

Parameter	
Operating Frequency (Hz)	<150Hz (This work 120Hz)
Amplitude of Current I_p	25 μ A
Internal Capacitance C_0	6.45 nF
Inversion factor	0.7
Output power	43.42 μ W
Performance Compared with Full Bridge Rectifier	3.36 x
Power Consumption	26 μ W
Chip Area	1.206*0.8 mm ²

Table 2. Comparison with state-of-the-art publications

Publication	JSSC 10 [1]	TPE 11 [6]	A-SSCC 13 [7]	This work
Process	0.35 μ m	Discrete	0.18 μ m	0.25 μ m HV
Operating Frequency (Hz)	225	185	200	120
Input Current Amplitude I_p	40 μ A	2mA	70 μ A	25 μ A
Piezoelectric Internal Capacitance C_0	12nF	330nF	25nF	6.45nF
Output power compared to standard	4x	2.3x	3.3x	3.36x

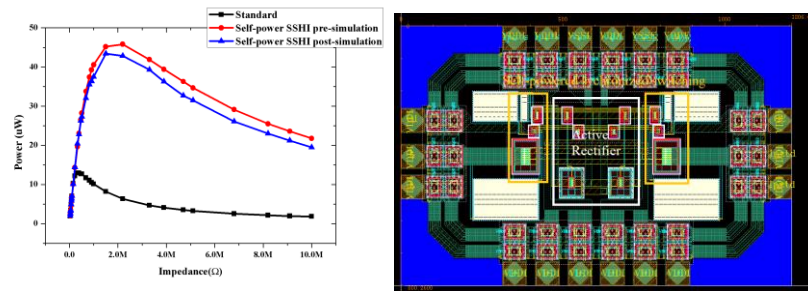


Figure6. Output power of the proposed P-SSHI circuit verses output impedance
Figure7. Layout diagram

5. Conclusion

This paper presented an integrated circuit design of a parallel-SSHI rectifier for piezoelectric energy harvesting, which can extract 336% more power than conventional full bridge rectifier with only 0.9648 mm² chip area. While operating with a self-made MEMS piezoelectric transducer with output current of 25μW 120Hz, internal capacitance 6.45nF, the output power can reach up to 43.42 μW. The maximum output power of conventional full bridge rectifier and parallel-SSHI is also studied and analyzed in this paper.

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Acknowledgments

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