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Analysis and Design of a Self-Powered VEH System Based on ULP Comparator

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Abstract—The study conducted shows a vibrational energy harvester (VEH) based on a microelectromechanical system (MEMS) with a gap-closing electrostatic resonator. The harvester system consists of a charge pump system in the form of a rectifier with feedback. An ultra-low power (ULP) comparator, based on a bulk driven topology, is connected to it, which regulates the harvesting cycle of the system. The complete circuit is implemented with 180 nm silicon technology. The designed energy harvester generates an output power of 65.45 nW at an acceleration of 0.35m/s² for a frequency of 53.5Hz. The implemented circuit is supplied with a voltage of one volt and shows a power consumption of about 7nW at the operating range. All simulations were conducted using Cadence Virtuoso. **Keywords**— Acceleration, VEH, MEMS, Comparator, ULP.

INTRODUCTION

The increase in demand for low-power consumption devices in recent years has caused an increased interest in energy harvesting systems. Among these, vibrational energy harvesters based on microelectromechanical systems (MEMS) are quite promising due to their small size and ability to supply applications with low power requirements. MEMS are good candidate for specialized applications such as Internet of Things (IoT) sensors [1], passive radio frequency identification [2], and biomedical devices [3], [4]. Applications of this kind require a continuous power supply that can maintain the equipment's operations. To do so, the MEMS must be able to operate at a wide bandwidth to allow them to function at the desired frequency range. In previous work, we have proposed a mechanical model and its electrical equivalent for an electrostatic nonlinear MEMS fabricated on SOI [5]. Based on this model we later designed a charge pump in Cadence Virtuoso in which we evaluated the voltage and power produced by this system [6].

The objective of the present study is to apply the MEMS model to design a VEH using a rectifier with feedback as the charge pump and an ultra-low power (ULP) comparator to control the energy harvesting process. An analysis is conducted to understand the operating points at the different parameters of the captured vibration frequency and acceleration, in order to 1) find the optimal capacitance and resistance of the components 2) to obtain the maximum DC output power and voltage efficiency, for the MEMS operating range.

The present work will be divided in three sections. The first section introduces the design of the fundamental blocks

that compose the VEH system. In the following section we assess the performance of the harvester device and improves the values of each component in order to peak efficiency. Finally, we evaluate the system response and power consumption to observe its voltage and output power in the selected range of frequency and acceleration. This is done to determine if the designed harvester is suitable for self-powered systems. Fig.1 shows the block diagram of the circuitry of the VEH we propose in this work..

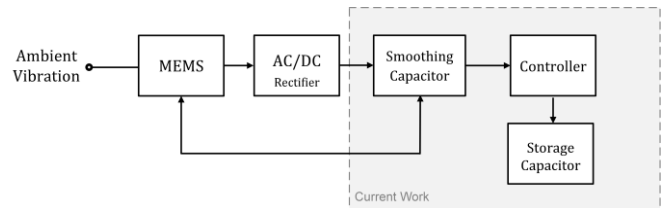


Fig. 1: Block diagram of the energy harvester.

In this work we decide to use 180nm node in CMOS techno that is a mature enough technology and offer reasonable low parasitic effects to reach a good assesment of the VEH performance. Such techno provides also a good feature for low power and hetero-integration. Therefore, for this study, a commercial technology (PDK) of 180nm is used.

IMPLEMENTATION

MEMS Model

The function of the vibrational energy harvester is to convert kinetic energy into electrical energy. As mentioned earlier, the device under study is a gap-closing electrostatic MEMS resonator. The geometrical and physical properties of the device are presented in [8]. The MEMS acts as a capacitor dependent on the displacement (x) with a capacitance C(x), shown in (1).

$$C(x) = \frac{2\epsilon SG}{(G^2 - x^2)} \quad (1)$$

Where ϵ is the dielectric permittivity of the medium (in F/m), S is the surface in m, G the gap size, and x is the displacement of the MEMS mass (M) in kg. The chosen values can be found in [8]. The MEMS is powered by a constant bias voltage (V_B). In most of the considered applications, the harvested ambient vibrations occur in a non-intentional frequency range; therefore, the frequency range

of the MEMS must have a wide capturing interval, referred to as the MEMS Band Width (BW). The internal displacement x is calculated through the mathematical model (2). Mechanical factors that affect the displacement of the device such as Damping (c), and Stiffness (K) are also considered.

$$M \frac{d^2x}{dt^2} + c \frac{dx}{dt} + Kx = \frac{4\epsilon SV^2 G}{(G^2 - x^2)^2} x + M\gamma \sin(\omega t) \quad (2)$$

This model was implemented and calculated in [5]. The value x is dependent upon the characteristics of the applied vibration, acceleration (γ) and frequency (f), and in the voltage of the MEMS (V). The MEMS structure is shown in Fig.2.

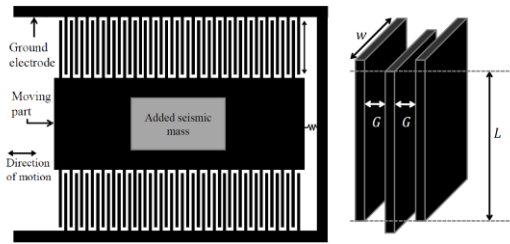


Fig. 2: Design of the gap-closing comb-drive electrostatic MEMS resonator. Physical characteristics are given, in [8].

Charge Pump design

The model of the MEMS is integrated into a charge pump electrical circuit. Given the oscillatory behavior of the MEMS, the charge pump requires a rectifier circuit to convert the AC signal produced by the transducer into a DC signal. The AC/DC converter uses a rectifier composed of two diodes (D1 and D2) and a smoothing capacitor C_L that also works as the load for the circuit. To perform the charging process, a part of the harvested energy is fed back through a diode D3. A precharged capacitor C_{bias} with voltage V_B is also incorporated in the circuit (in Fig. 3).

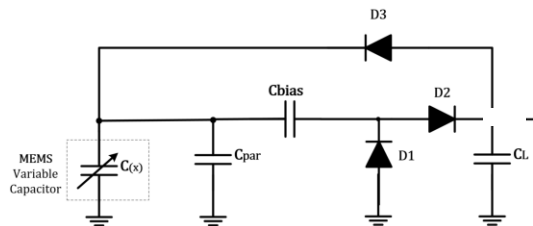


Fig. 3: Circuit for charge pump.

The circuit uses a rectifier (D1, D2) so that the generated electrical energy is accumulated in C_L . C_{bias} must be much larger than $C(x)$ for the entire displacement range of the moving frame (0 to 50 μm) so that voltage ripple at the output can be canceled out during each conversion cycle. The energy harvester operates by receiving the AC voltage produced by $C(x)$ and rectified by D1 and D2 to produce a DC voltage at the load. The rectification operates as follow. First C_L accumulates charge until it produces a voltage drop greater than that of $C(x)$. Then the DC voltage is transferred back to $C(x)$ charging the capacitors $C(x)$ and C_{bias} , while losing some of the charge in C_{par} . When $C(x)$ has a voltage greater than C_L , D3 will go into operation causing the cycle to repeat. Given its closed-loop structure, the energy

harvester stabilizes at the same operating point, regardless of the initial V_B , if it provides sufficient power to start. The steady-state bias point will depend upon the frequency, acceleration, and load value. Given that, $C(x)$ is at the maximum displacement of 45 μm , 90% of the gap, is 32.42pF. A load C_L of 33nF is chosen in consistency with previously used in the literature for this type of application [3]. The insulation resistance of C_L is chosen based on a previous work [9].

Power management unit

Due to the limited power output of VEHs, energy efficiency is vital for these systems. Therefore, it is essential to use a voltage comparator with very low power consumption in the energy management unit. Other design constraints we have are a rail-to-rail output voltage range of? and continuous operation without a clock. To compensate we used a comparator structure, implemented in [10] where they use a twin-well 130 nm CMOS technology and featuring a power consumption of less than 250nW. For this current work, the structure is resized and implemented using 180nm technology. The transistor-level schematic of the comparator is shown in Fig. 4.

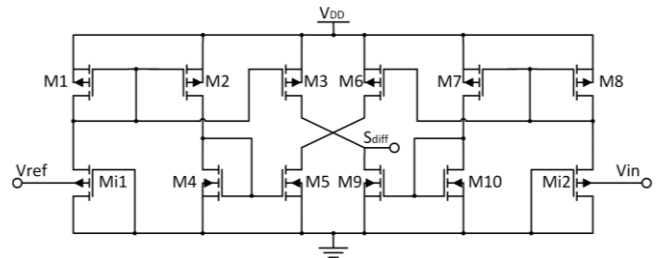


Fig. 4: Comparator Circuit

The topology is based on incorporating gm/ID design methodology by using a bulk-driven structure. Therefore, the inversion of the MOS devices used is limited to a weak inversion (subthreshold). This design strategy has been previously implemented in [10-12], showing promising results for ultra-low power applications. The bulk-driven input stage effectively eliminates the threshold voltage problem of the MOS devices and allows rail-to-rail operation [10]. Devices M_{i1} and M_{i2} act as constant current sources whose amount of static current is being modulated by the input voltage according to the body effect phenomenon. This voltage-to-current conversion occurs linearly, since the transconductance $g_{mbs} = (\partial I_D / \partial V_{BS})$ is almost perfectly constant over the entire specified voltage range. In addition, there is no internal bias reference in the circuit, which simplifies the design procedure and reduces the total current consumption [10]. Fig.5 presents the I_D current for transistors M_{i1} and M_1 as a function of input voltage i . Since the current is inversely proportional to the bulk voltage, above 2.2 volts, the I_D current will be sufficiently low preventing current flowing between M_1 and M_{i1} , causing the comparator to fail to operate.

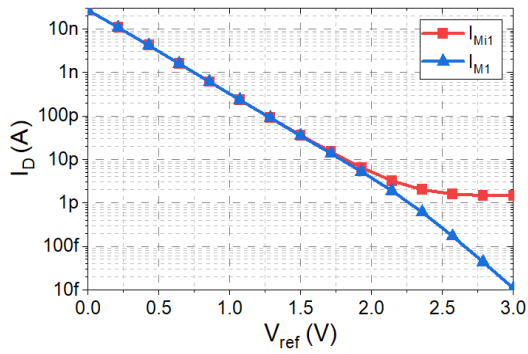


Fig. 5: Curve of current vs Vref for transistors Mi1 and M1.

For practical implementations, the energy stored in the CL capacitor is used intermittently, repeating charge and discharge cycles utilizing the power management circuit. The complete circuit (Fig. 6) consists of an ULP comparator and an N-type MOSFET. The NMOS functions as a normally closed switch, and the intermittent switching is controlled by the comparator. When the NMOS is in saturation, the current flows charging the capacitor Cstorage. This circuit also regulates the output voltage to a range of 2 to 5V for powering subsequent circuits; reducing the standby current but increasing the source current. The harvester circuit schematic is shown in Fig.6.

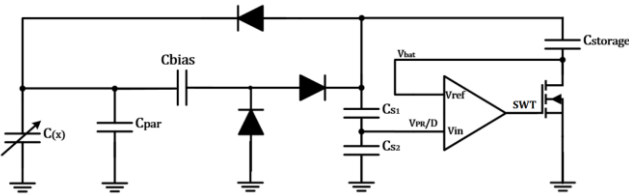


Fig. 6: Circuit for MEMS-based energy harvester.

The switching is controlled based on the voltage $V_{in} = VPR/D$, where VPR is the voltage at the MEMS and D is the optimization factor, compared to $V_{bat} = VPR - V_{CStorage}$. Factor D is controlled as a function of the capacitances Cs1 and Cs2, whose total capacitance is equal to CL, which function as a capacitive voltage divider. The insulation resistance of these capacitors is recommended to be equal to or greater than 1GΩ, this value of optimum resistance was calculated in a previous work [9]. Comparable power management circuits were developed in prior papers [13-16].

The Simulation in Virtuoso allows to obtain a steady-state response for a $D = 3.75$ at a frequency of 56Hz with an acceleration of $0.3m/s^2$ of the Harvester as presented in Fig. 7.

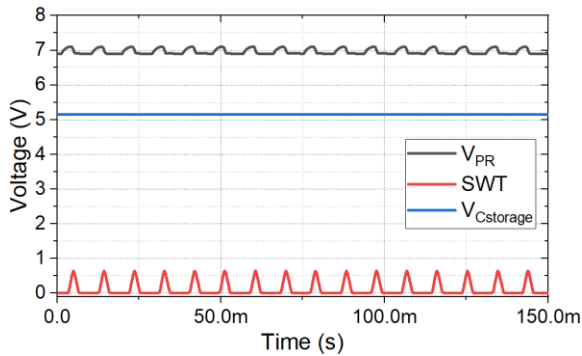


Fig. 7: Steady State response of the Harvester Circuit.

The response of the comparator (SWT) is intermittent thus keeping the MEMS voltage and $V_{CStorage}$ stable.

PERFORMANCE EVALUATION

Circuit Optimization

Optimization is carried out by sizing the components characteristics. In this method the power value at each of the different frequencies is determined by applying the different values of D. The obtained results are presented in Fig. 8.

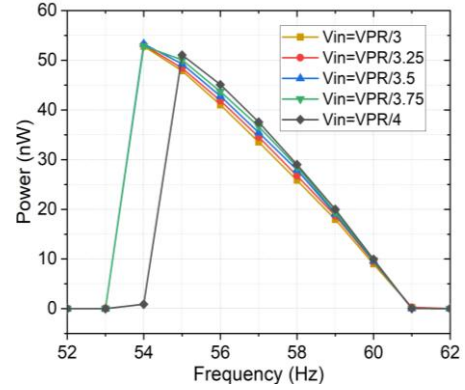


Fig. 8: Value of the Power at the Storage Capacitor.

It can be seen in Fig. 8. from a value of $D = 3$ to $D = 3.75$ the optimum power value was reached. Given the limitation that exists in the input voltage of the comparator, it is recommended to have the maximum possible value of D so that the input can be reduced while maintaining the output power.

Results and discussion

The simulation is performed using a factor $D = 3.75$. For Cs1 and Cs2 with an insulation resistance value of 10GΩ. The results are shown in Fig. 9.

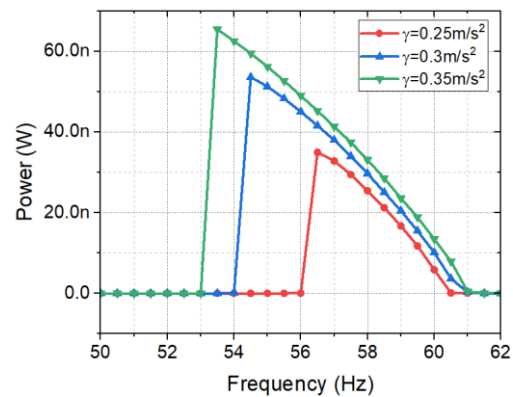


Fig. 9: Value of the Power at the Storage Capacitor at different accelerations.

The analysis shows that the VEH using the charge pump designed with $0.18\mu m$ technology produces a power of $65.45nW$ at $0.35m/s^2$ at 53.5Hz.

Power consumption for the harvester circuit was determined at a constant voltage supply of 1 volt. The circuit presents an average power consumption of $7nW$ in the range of operating frequencies for each acceleration. Due to the selected system structure, the system has higher power consumption when the input voltages of the comparator are

lower. This is reflected for all cases at frequencies below 52Hz and above 61Hz. Results are shown in Fig. 9.

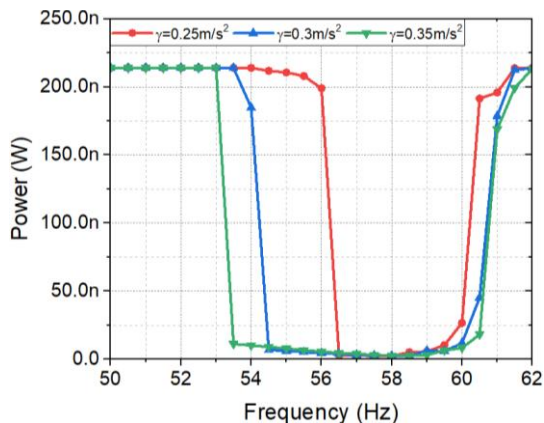


Fig. 10: Power Consumption of the system at different accelerations.

COMPARISON OF HARVESTING CIRCUITS

Reference	[13]	[14]	[15]	[16]
Switch Type	CMOS	MEMS	CMOS	CMOS
Harvester Type	PE	ES	-	PE
Operation Voltage	1.59V	3V – 5V	1V	1.85V
Power Consumption	-	Negligible	12 mW	0.5 uW

PE: Piezo Electric, ES: Electrostatic, -: no information provided

Table I compares recent work on MEMS-based harvesting circuits from the point of view of operating voltage and power consumption. It must be pointed out that the comparison between harvester circuits is problematic since several factors must be considered, such as MEMS type, harvester area, bandwidth, and operating acceleration. Among the types of harvester circuits, we can find switching that can be electronic, usually implementing a comparator [10,13,15,16], or mechanical using a MEMS to generate the intermittent signal that charges the load capacitor [14]. The mechanical structure has lower power consumption since it does not necessarily need current to operate although the implementation becomes more complicated. The harvesting circuit for this work uses electronic switching based on the ULP comparator. The circuit had an average power consumption of less than 7nW for an acceleration of 0.35m/s² in the operating range of 52Hz to 60.5Hz.

CONCLUSION AND FUTURE WORK

In this paper, a harvesting circuit based on an Electrostatic MEMS fabricated in SOI was designed and simulated. The voltage control is performed by using a Charge Pump that rectifies the output signal of the MEMS and recharges it. An ULP comparator that functions as closed loop controller is in charge of the harvesting control. The complete circuit was implemented with 180 nm silicon technology. A switch in the form of an NMOS is inserted between the charge pump and the storage capacitor. This switch is activated when the voltage exceeds a set point; when the voltage exceeds the set point, the switch closes charging the storage capacitor and discharging Cs1 and Cs2. The implemented circuit is fed with a voltage of one volt and shows a power consumption of about 7nW for the operating range.

Using this harvester circuit, a maximum power output of 65.45 nW is achieved at an acceleration of 0.35m/s². Unlike most of the electronic harvester circuits previously presented in the literature, the current circuit presented in this work has extremely low operating current consumption making it ideal for energy harvesting implementations. This is due to the bulk driven topology presented in [9]. Drawbacks presented by this technology are observed in the manufacturing part due to the need for Twin-Well manufacturing and the limitations in the input voltage.

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