Energy Harvesting based on a Low-Cost Piezoelectric Acoustic Transducer

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Abstract—**This paper describes an approach for harvesting electrical energy from a low-cost piezoelectric element using a CMOS energy processor. The converter consists of an ordinary piezoelectric buzzer and a steel ball bonded onto it. The device mechanically behaves as a spring-mass system. Mechanical vibrations are converted into electric power by a PZT layer. Furthermore, the design of the CMOS energy processor is presented and its simulation results are discussed. The processor has the function of controlling the charge delivered to a 1.2Vdc battery**

Keywords-energy harvesting, piezogenerator, piezoelectricity, low power.

I. Introduction

Semiconductor devices technology experimented an astonishing increase in the scales of integration over last decades. Consequences are visible in the "ubiquitous" cell phones, PDAs, portable stereos, notebooks, and other electronic goods. With several disposable technologies for digital signal processing, sensors, and wireless communications, applications as sensor networks, monitoring of tire pressure and pervasive computing came into research focus. One of the most challenging issues in this area is the production energy sources that can supply enough power for wireless communication of sensed data. Investigation has focused on batteries and ambient power scavenging to provide power for sensor networks. Energy harvesting alternatives ranges from thermal energy to mechanical vibration. Among several power-generating options, piezoelectric vibration-based systems seem to be an attractive and practical solution, combining good power density and availability of primary source..

II. Circuit Description

Depending on mechanical vibrations amplitude and material characteristics, piezoelectric ceramics should produce alternate voltages ranging from hundreds of milivolts to dozens of volts.

In [1,2] was performed a study about the vibration level of different vibration sources and one can see that the majority sources has amplitude around dozens to hundreds of milig ($g=9{,}81 m/s^2$).

Using piezogenerator to converter mechanical to electrical energy one can use different ways. First, in the generator using especial piezoceramics [3] with high factor conversion but with high cost. Other way is using cheap material (like unimorph buzzer) [4] maximizing the conversion by using mass bonded to the piezoceramic. In the fig.1 is shown the piezogenerator of [4] and in the fig.2 the arrangement of buzzer . This configuration generated voltage around hundreds of milivolts at low vibration amplitude (dozens to hundreds of milig).

A vibrating piezoelectric device generates an ac voltage while electrochemical batteries require a DC voltage, hence the first stage needed in an energy harvesting circuit is an ac–DC rectifier connected to the output of the piezoelectric device. Furthermore the vibration amplitude may be not constant so the voltage generated will be inconstant too. This creates the need for flexibility in the circuit, i.e., the ability to adjust the output voltage of the rectifier to achieve maximum power [5] .To facilitate the attainment of the optimal voltage at the output of the rectifier, a charge control control should be placed between the rectifier output.

In this way one challenging is design one charge control to maximize the flow of electrical power from piezogenerator to storage devices (like battery or capacitor) that operate at low voltage (like <= 0.7Vdc) and ultra low power consumption (hundreds of nW). Conventional technologies means CMOS 0.35µm, 0.25µm and 0.5µm has a high threshold voltage. So the charge control circuit will be operate in region called sub-threshold. In this region the parasitic component has expressive value. To avoid this problem one can use voltage doubler rectifier structure to generate sufficient voltage to the charge control circuit. This structure can be developed using traditional topology (fig.3) or with floating gate structure [6]

A challenging task is converting minimum energy amounts to suitably charge a battery or a capacitor, and use it for powering electronic circuits. In this paper, we discuss and simulate a CMOS power processor with the functions mentioned above, analyzing its use in real world applications.

A. Generator

The energy scavenging system includes an electric power generator (PZT transducer – Buzzer), a storage device (Battery), and CMOS energy controller (IC) (fig.5) , as shown in the block diagram of fig.1. The system is electrically self powered and is designed to have the least power lost as possible.

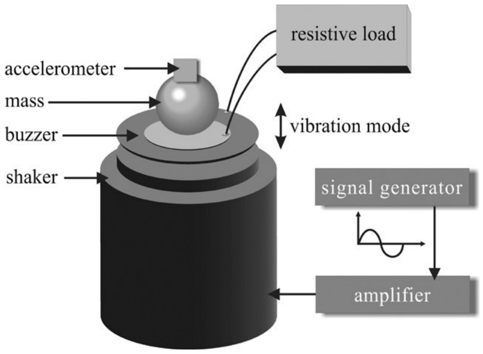

Fig. 1. Harvesting Circuit used in the experiences

Fig.2 shows the buzzer with the following dimensions: Rmetal=20mm, Rpiezo=12.5mmetal, hpiezo=0.25mm, hmetal=0.25mm.The mass bonded has value of 30g.

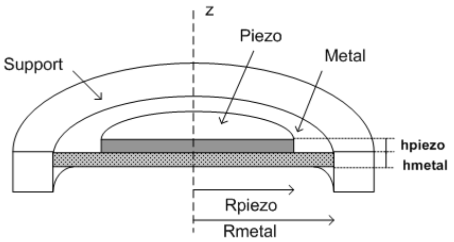

Fig.2 Buzzer used in the experiences

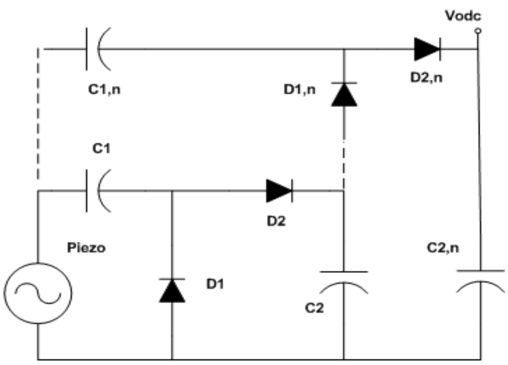

Fig.3– Traditional voltage doubler rectifier structure

The piezogenerator was simulated in the ANSYS to found the natural resonant frequency, the resonants modes and his deflection amplitude. In the fig.4 one can see the first two frequency. Typically, the first frequency generate more energy than another frequencies because in this frequency occur the biggest deformation and so more electrical voltage.

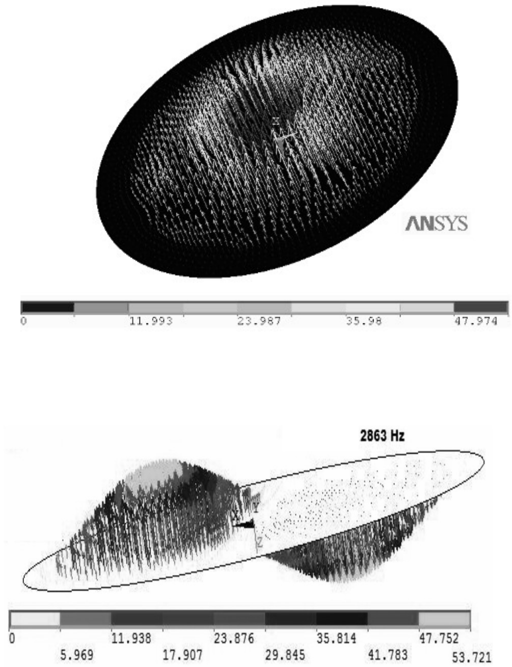

Fig. 4. ANSYS simulation of the first two resonant modes of the piezoelectric buzzer.

B. Charge Controller:

When the battery voltage is below 2 V, it is loaded through MOS transistors tied diode of the voltage doubler rectifier. The control circuit works to keep the battery voltage around 2V. This control is necessary because when the PZT (buzzer) is impacted it can generate high voltage peaks, which could cause battery damages.

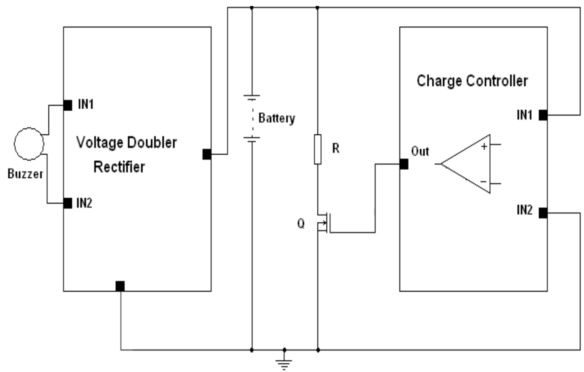

Fig.5– Block Diagram of Integrated Circuit

III. Voltage Doubler Rectifier

This stage is fundamental to maximize the efficiency of the proposed energy harvesting. The number of stage depends on the technology used and output voltage desired. Newest technology (like CMOS 0.13µm) have lower threshold voltage and so the number of stage will be lesser than in the CMOS 0.5µm by example. However, your price it is biggest.

To safe silicon area one possibility is use o MOSCAP better than poly-poly2 capacitor as it was described in [7,8], the design should be attempt to the no-linearity of capacitance how function of the polarization. In fig.2 the capacitors C2 to C2,n may be implemented how MOSCAP because they have a fixed potential (ground) in one terminal. Capacitors C1 to C1,n should be implemented in poly-poly2 capacitors.

One of the important trade offs in the design of the voltage doubler rectifier is the size of the transistor versus parasitic capacitance [9,10]. Than smaller area, less parasitic capacitance, however, rectification efficiency is lowered by the smaller transistor size since smaller transistor can deliver less current to the load. The transistor sizes can be reduced to a few times the minimum width to reduce parasitic capacitance as seen from the input of the rectifier, however, the reduction in channel width may cause a decrease in the performance of the rectifier due to the increase in the channel resistance of the diode-tied transistors.

As the number of rectifier stages increases, the capacitive component in the rectifier input impedance increases thus reducing the reactive component of the rectifier input impedance. With this, the maximum voltage gain that can be achieved at the input is also decreased at the same rate since the resistive component in the input impedance stays fairly constant.

The trade off between the transistor sizes used for rectification versus the number of rectifier stages should be established.

IV. Experimental Procedures - Generator

The schematic diagram of the experimental apparatus for measuring the input vibration and output electrical energies is shown in fig.1. The energy converter we have developed consists of a steel ball with a known mass, attached onto an ordinary piezoelectric buzzer. It is submitted to controlled vibrations generated by a moving coil shaker. The input energy is computed from the acceleration measurement, performed with an Analog Devices ADXL 302. accelerometer (sensitivity:1V / G , precision 1mG, where G is the gravity acceleration). An Agilent Digital Oscilloscope 54622 A was used to measure the voltages from accelerometer and buzzer outputs.

Three sets of experiments were performed:

First set of measurements were performed with different values of resistive loads at generator's output: from 5.0 kΩ to 48kΩ. The power output was measured while the frequency was swept in order to determine the maximum output condition.

Then, the input frequency was set to 130 Hz and the resistance connected to the output terminals was changed for seeking the maximum power transfer condition.

Second: the output power is characterized as function of vibration amplitude and resistive load, with fixed frequency.

Third: the output power was measured as a function of the resistive load and type of support. In both experiments, the shaker was driven with a sinusoidal voltage, obtained from an Agilent 33120A function generator with its output boosted by an integrated audio amplifier (National Semiconductors LM3875).

A. *Generator:*

The electrical output power of the piezoelectric energy converter was measured for sinusoidal input vibrations with variable amplitude and fixed frequency (130Hz)

The value of this frequency was obtained by varying the function generator and fixing the value of the resistive load

Measurements results are shown in fig.6. The maximum output power was obtained at load resistance of 14 kΩ. The maximum achieved output power is 53.2µW, at a=4m/s^2, for a resistive load of 14 kΩ.

Fig. 8 and fig.9 is presented the result of measurements of power generated by piezogenerator as function of acceleration and the effect of the support in the power and resonant frequency.

In the mechanical parts of generator is possible adjust the resonant frequency changing the form of the support. Fig. 8 and 9 shows the effect of the support in the resonate frequency and power generated.

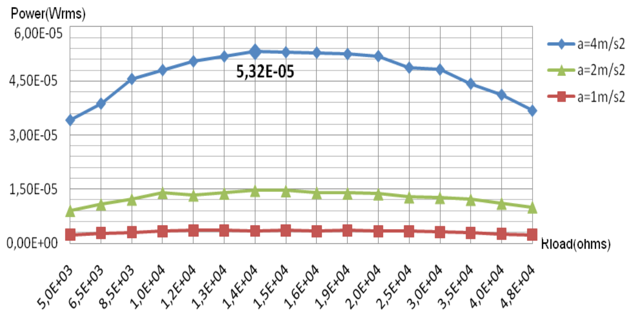

Fig.8. Measured power versus resistive load versus acceleration

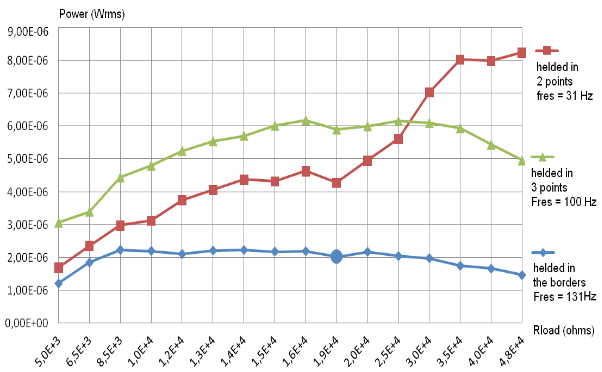

Fig. 9. Measured power versus resistive load versus support

The conversion efficiency can be calculated by dividing the electrical output of the mechanical input energy. The mechanical energy converted from potential to the kinetic over the course of half oscillation period (T/2), can be approximated by:

$$Wmec = 0.5 \times m \times v^2 \quad (1)$$

where m is the mass attached to the buzzer and v is its maximum speed.

The velocity is obtained by integrating the acceleration waveform. The maximum speed for a body oscillating at 130 Hz, with acceleration amplitudes of $4 m/s^2$ is:

$v = 4.9 \times 10^{-3}$ m/s . The resulting mechanical energy is:

$W_{mec} = 0.36$ µJ (m=30g).

The electrical energy :

$Welet = 53.2 \times 10^{-6} \times (0.5 \times (1/130Hz)) = 0.2$ µJ

The efficiency can be obtained as:

$$\boldsymbol{\eta = Welectric / Wmecha} \quad (2)$$

$$\boldsymbol{\eta = 0.57}$$

B. Integrated Circuit – Simulated Results

The Charge Control Block it was discussed in [4]. When the voltage of the storage device is below 2 V, it is charged through the voltage doubler rectifier. Above this threshold, the control circuit works to keep the voltage around 2V. This control is necessary because the PZT should generate high voltage peaks when impacted, which could damage the battery.

To the voltage doubler rectifier were performed simulations with different transistor areas and different capacitances for safe silicon area. The simulations showed that the best

configuration was capacitors with capacitance of 10pF and the MOSFET transistor with W=120µm and L=0.7µm.

The simulations results of the voltage doubler rectifier it is shown in table 1 for different technologies (in µm) . The term V1 to V25 are referred to output voltage of stages in volts DC.

Tech	V1	V3	V7	V10	V15	V17	V20	V22	V23	V25
0.5	6.2m	0.2	0.6	0.87	1,37	1.57	1.86	2.1	2.3	2.5
0.35	0.11	0.32	0.73	1.04	1.54	1.75	2.05	2.25	2.32	2.51
0.25	86m	0.19	0.79	1.13	1.63	1.84	2.14	2.34	2.44	2.64

Table 1. Simulated value of voltage double rectifier

V. Conclusions

This paper analyzes the output performance of an energy harvester consisting of a piezoelectric generator and a CMOS energy processor. The piezoelectric generator is assembled with a low-cost piezoelectric buzzer and uses mechanical vibrations as input. Its response was measured as a function of the input vibration frequencies and output load resistance. The best efficiency obtained during the tests was 57%. The efficiency and amount of generated energy of the low-cost converter is comparable to other models, indicating that it could be used in some applications where the miniaturization is not important and low price is desirable.

In this work it was perceived that differently of [6] it possible have a better efficiency with the first transistor tied diode with NMOS transistor and not all PMOS transistor.

The power processor integrated circuit has been simulated and layed out with Mentor Graphics Design Architect, using AMI 0.5 µm CMOS process. The voltage doubler rectifier with 25 stages it occupied most of the area with $0.792 \times 0.332 mm^2$ and the layout is shown in fig.10.

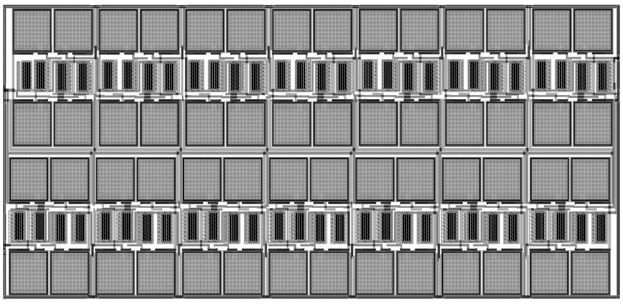

Fig.10– Layout of Voltage Doubler Rectifier

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