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Integrated power harvesting system including a MEMS generator and a power management circuit

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Abstract

This paper presents a novel ambient energy scavenging system for powering wireless sensor nodes. It uses a MEMS generator and an ASIC power management circuit. The system is created as a System on a Package with all components fabricated entirely using microfabrication techniques. Its performance is compared with standard approaches using a resistive load or discrete Schottky diodes. The electromechanical transduction is performed using the piezoelectric effect of aluminium nitride thin films. The reported experimental results prove the possibility of exploiting very low amplitude signals delivered by the generator for charging a storage capacitor. It is also shown that a system of 5 mm^3 can endlessly power a simple wireless sensor node; while a lithium polymer thin film battery of the same volume can do so only for less than 2 months.
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Keywords: Piezoelectric MEMS; Autonomous microsystem; Ambient energy harvesting; Wireless sensor nodes

1. Introduction and motivation

1.1. Ambient energy harvesting

The future development of wireless sensor networks is conditioned by the availability of small but long lasting power sources for its nodes. Ambient power harvesting is a possible breakthrough in this domain [1–4]. It gives the possibility of reducing the size of the local energy reservoir, which no longer needs to contain energy for the entire lifetime of the device but only for several cycles of its activity. Many possible applications require small size, so miniaturization of the energy scavenging system by the use of microfabrication techniques is crucial. We have chosen to explore the possibility of converting the energy of environmental mechanical vibrations into useful electrical energy. This ambient energy source is easy to use by the means of a simple mechanical coupling and moreover proposes high energy densities [5]. The energy of ambient mechanical vibrations can be converted to electricity using three methods: electromagnetic, electrostatic and piezoelectric. The first method offers the best energy density, while the electrostatic method is the least effective in this respect [5]. The requirement of miniaturization excludes the use of electromagnetic effect, which not only needs high quality magnets and low resistance coils in order to work efficiently, but also delivers very low amplitude signals [6]. A device using the electrostatic conversion method can be relatively easily build using microfabrication techniques, but requires high voltages of operation and a special polarisation circuit [7]. Some novel solutions were proposed, like the use of electret thin layers [8] but this eliminates the principal advantage of this solution being the simplicity of construction and compatibility with CMOS process. Finally, a device using the piezoelectric conversion method can be miniaturized, but requires high quality piezoelectric thin layers in order to work efficiently. Thanks to the recent progress in this domain, the properties of piezoelectric thin layers are close to the ones obtained for bulk materials [9,10]. We have therefore decided to explore the possibility of building a micropower harvesting system employing the piezoelectric effect.

1.2. Energy scavenging system

The energy transducer device that will be used to convert the energy of ambient mechanical vibrations to electricity will provide alternating, low amplitude signal. In order to make use of the generated energy, an energy scavenging system must be employed. Fig. 1 presents a schematic of the proposed system. It contains a transducer (in our case a piezoelectric MEMS

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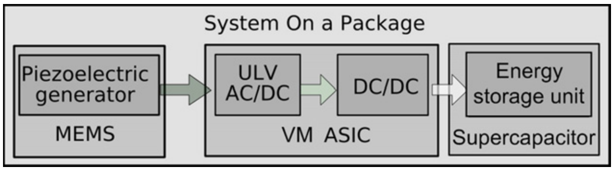

Fig. 1. Schematic of the energy scavenging system composed of a MEMS piezoelectric generator, a custom ASIC containing the voltage rectification and amplification circuits as well as an energy storage unit.

device), an ultra low voltage (ULV) rectification and voltage multiplication (VM) circuits and finally an energy storage unit.

In recent years a number of researchers have proposed innovative solutions for power extraction from piezoelectric elements. These were either adaptive methods [11] or active synchronised methods [12]. In spite of their efficiency, their application is limited to systems with relatively high power outputs. It is caused by the need of powering the extraction system itself and the use of standard diodes for rectification. A system adapted for very low powers is proposed by Le Triet et al. [13], where active and passive methods are explored for power extraction from a resonant piezoelectric membrane. Authors of this paper conclude that the active rectification method is more efficient. Nevertheless, it is stated that in case of use of diodes with very low-threshold voltage the passive approach can prove to be more efficient.

In this work, we propose a system that incorporates a MEMS power generator delivering very small powers (in the nW–μW range) at voltages often inferior to 200 mV. A custom, passive power management circuit is used to charge a storage capacitor from which power is delivered for one cycle of activity of a very low power wireless sensor node, operating at very low duty cycle. All the components of the system are created using CMOS compatible batch microfabrication techniques. Finally, we propose to implement the device as a System on a Package (SoP) in order to reduce its size and the cost of fabrication.

2. MEMS generator

The presented system incorporates a MEMS micropower generator (μPG) that uses the piezoelectric effect for converting the energy of ambient mechanical vibrations into useful electrical energy. The active piezoelectric material is a thin layer (1 μm) of aluminium nitride (AlN), deposited by reactive magnetron sputtering directly on an SOI substrate. This piezoelectric material is inferior to PZT in the means of coupling coefficient but its deposition is relatively simple, compatible with microelectronics and does not require polarisation. The schematic view of the layer structure of the device is shown in Fig. 2. The top layer of the SOI wafer is highly doped with boron which reduces its resistivity and therefore permits its use as the bottom electrode for the piezoelectric capacitor. This solution reduces the complexity of the process flow, but induces creation of parasitic capacitances between the silicon layer and each top metallization. The geometric structure is created by both sides deep reactive ion etching (DRIE) using the buried SiO_2 as the stop layer. The dimensions of the proposed structure are an outcome of an optimisation process using the previously presented FEM and analytical models [14]. These are cantilever beams with seismic masses that are 1200 μm long and 800 μm wide. The thickness of the mass is equal to the thickness of the SOI wafer used (525 μm). The thickness of the cantilever beam is equal to 5 μm. Fig. 3 presents a SEM picture of the fabricated device.

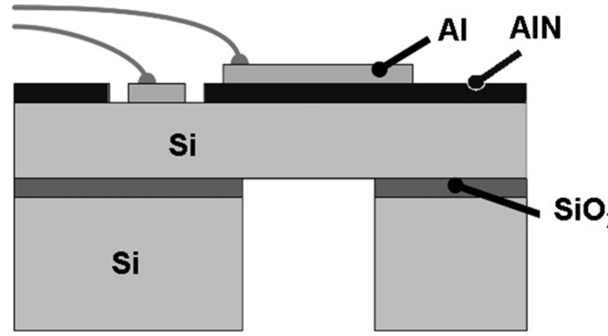

Fig. 2. Layer sequence of the AlN micropower generator.

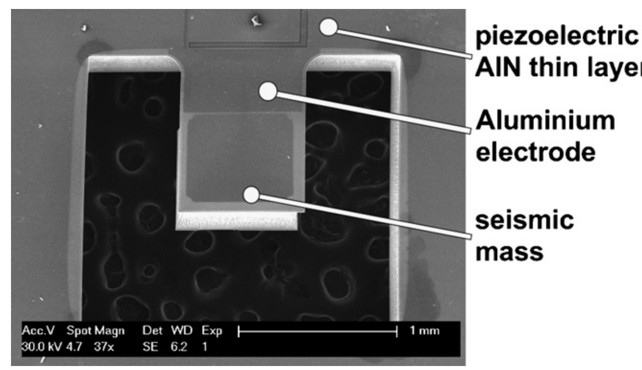

Fig. 3. SEM photograph of the fabricated piezoelectric MEMS vibration energy scavenger.

We have analyzed performance of the proposed micropower generator using ANSYS^{TM} FEM software. Figs. 4 and 5 present,

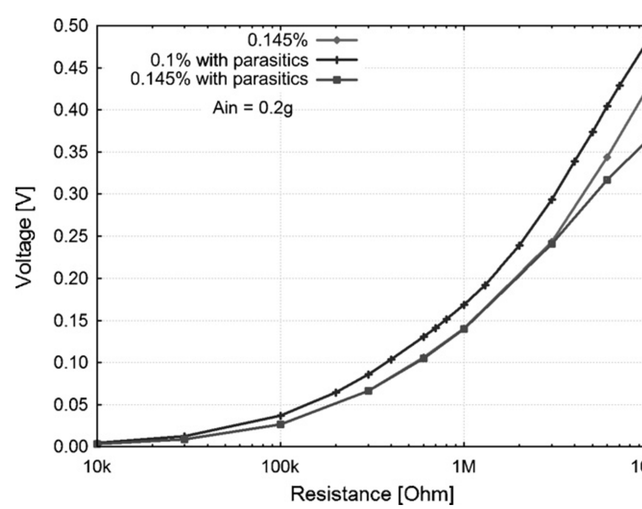

Fig. 4. FEM simulation of the voltage generated by one MEMS AlN microgenerator vs. the load resistance value, for different values of constant damping ratio (percentage of the critical damping) with and without the inclusion of parasitic capacitance.

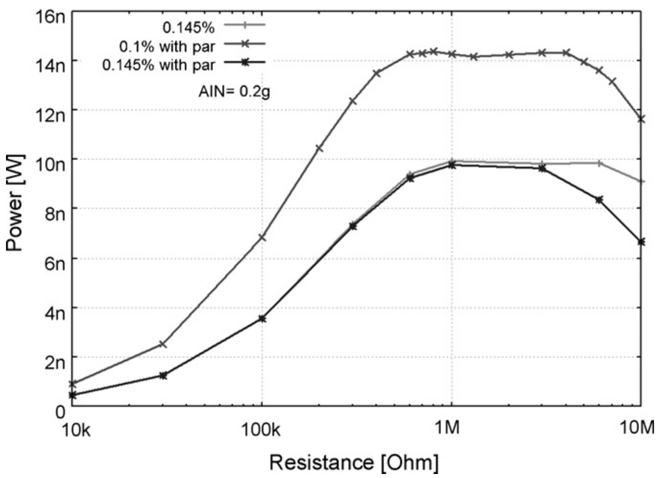

Fig. 5. FEM simulation results of power generated by one AlN device vs. the resistive load value, for different values of constant damping ratio (percentage of the critical damping), with and without the inclusion of parasitic capacitance.

respectively results of simulation of output voltage and power versus resistive load value for different levels of viscous damping in the system, represented as a percentage of the critical damping. The device is operating at resonance of about 1580 Hz with $0.2 \times g$ input excitation. The influence of the already mentioned parasitic capacitance is also introduced. It can be seen that powers of about 10 nW can be obtained at resonance from one device at very low excitation levels of $0.2 \times g$. The presence of parasitic capacitance reduces the coupling of the system and therefore also reduces the generated power. The output voltage increases with the load resistance value and there exist one or two optimal load values, respectively for low and high coupling levels [14].

3. Power management circuit

The power management circuit consists of two elements: an AC/DC converter which rectifies the alternative signal delivered by the generator and a DC/DC converter adapting the levels of voltage to the storage element characteristics and the requirements of the client electronics. As shown in Fig. 4, the output voltage of the MEMS generator is often smaller than the threshold voltage of diodes used in conventional rectification circuits.

Furthermore, the amount of power that is lost during rectification is proportional to the threshold voltage of the diodes used. To overcome this obstacle we propose novel low-threshold voltage diodes based on MOS transistors. These diodes are then used in the design of a voltage multiplier circuit (VM). Our system generates very low powers, so we decided to use completely passive circuits. This solution offers lower efficiencies than the active one, but it does not need to be powered and is therefore more suited for ultra low power applications [11,13]. The system will be used to charge a storage capacitor. We have chosen supercapacitors rather than batteries as the local energy reservoir because of the simplicity of their charging process and the possibility of withstanding much more charge–discharge cycles. This element will be used to store the harvested energy and to deliver high power output during the short period of activity of the electronic circuits of the wireless sensor node.

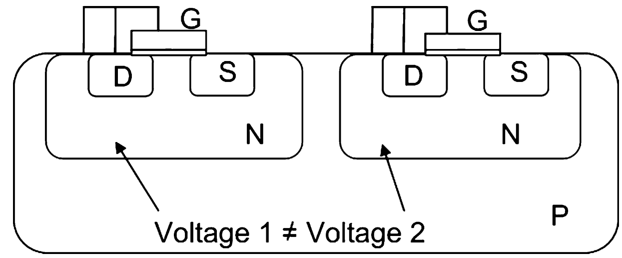

Fig. 6. Schematic of the proposed DTMOS transistors used as very low threshold diodes.

3.1. Low-threshold voltage diodes

The proposed diodes use DTMOS transistors (dynamic threshold voltage MOSFET). The idea of their operation is based on the connection of the gate, the drain and the bulk of the transistor together in order to obtain diodes with low-threshold voltage (Fig. 6).

PMOS transistors were chosen because of the facility of separating their bulks and therefore a possibility of varying their potentials. We used the 0.13μ HCMOS9 technology from STMicroelectronics to fabricate the circuits. Fig. 7 presents the results of characterization of one such device. Each diode is in fact an optimised transistor with channel width of 5 μm and length of 0.3 μm. For very low currents, corresponding to those generated by the piezoelectric transducer, the value of the threshold voltage is lower than 200 mV. The reverse current was experimentally measured to be about 90 pA at 1 V polarisation.

3.2. Voltage multiplier

Fig. 8 presents structure of a voltage multiplier circuit based on cascaded Villard voltage doublers [15]. It is used to rectify and increase the generated voltage at the same time. The circuit

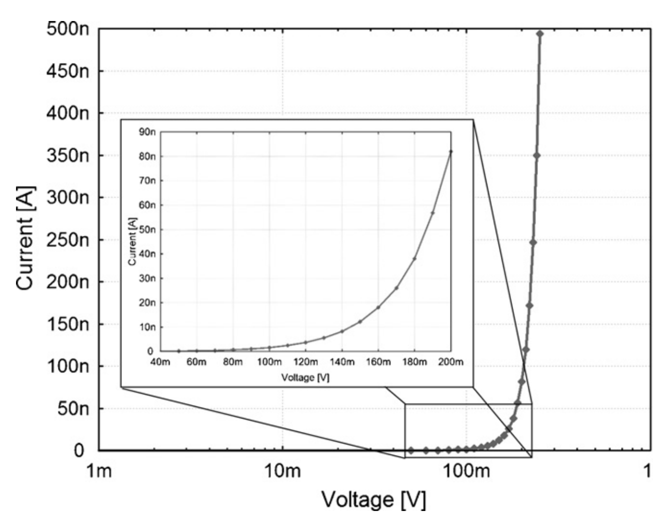

Fig. 7. Current–voltage characteristic of the proposed integrated, ultra low-threshold voltage diode.

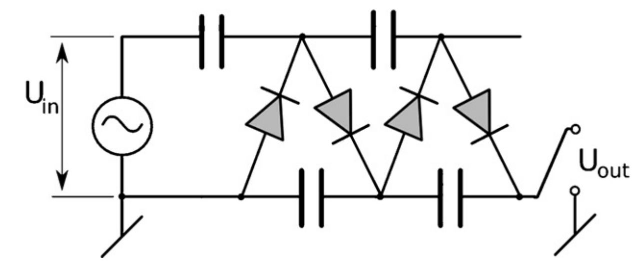

Fig. 8. Conventional structure (Villard) of a voltage multiplier with two multiplication levels.

functions as follows: for the negative peak, the top left capacitor is charged to a voltage equal to the input voltage amplitude, then for the positive peak the voltage on this capacitor adds to the input voltage and the bottom left capacitor is charged to two times the input amplitude. This procedure is repeated for the entire cascade. Charging of all capacitors to their maximal voltages may therefore take many periods of the input signal.

If we replace the standard diodes with the proposed low-threshold voltage ones, we obtain a voltage multiplier that can accept very low amplitude signals at the input. The efficiency of this circuit is related to the amplitude of voltage provided by the microgenerator and the number of levels. We were limited to 1 mm^2 of silicon surface and the fact that the maximum value of a single capacitor that can be realised in the technology used is equal to 40 pF. We decided to implement a voltage multiplier structure with six multiplication levels.

4. System on a Package

In order to reduce the size and cost of the power scavenging system, we decided to implement it as a System on a Package (SoP). Fig. 9 presents the realised SoP containing the piezoelectric MEMS micropower generator and the voltage multiplier circuit. The device does not require any external components to charge a storage element. The total volume occupied by

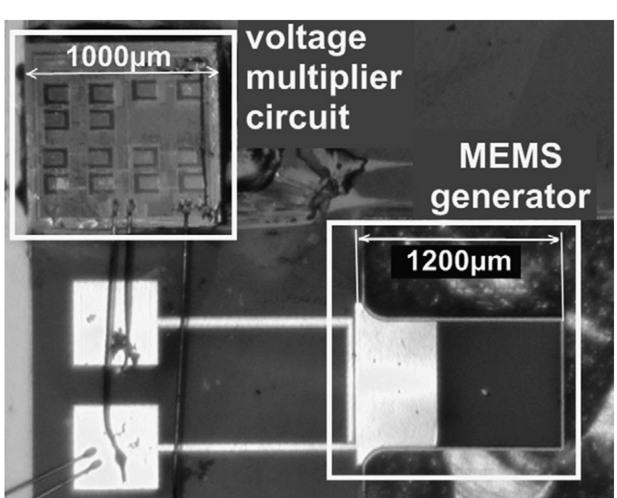

Fig. 9. Photograph of the proposed system containing the voltage multiplier circuit and the piezoelectric MEMS power generator.

the assembly can be estimated at several cubic millimetres. It can be reduced however to 1 mm^3 after optimisation. An ultimate integration would be a System on Chip (SoC) where the ASIC circuit and MEMS generator would be realised on the same silicon substrate. Nevertheless, we judge that such realisation would be too complicated from the technological point of view and as there would be no significant advantage over a SoP device, this approach would be economically unjustified.

5. Experimental results

To characterize the created micropower scavenging system, we used a controlled vibration source, composed of a VM20 shaker and PA100E amplifier from Data Physics. The output voltage was observed through a very high impedance instrumentation amplifier Burr-Brown INA116. The excitation acceleration was controlled in closed loop and the results were recorded using a custom LabVIEW application.

5.1. Power generated on a resistive load

In order to explore the performance of the MEMS power generators, the output power was in the first place analyzed on a resistive load connected directly to the electrodes of the piezoelectric element. An optimal value of the load, for which the power generated on this load is maximal, was determined to be 450 kΩ. We performed an analysis of output power and voltage generated on this matched resistive load at resonance, for different acceleration levels.

Fig. 10 presents output voltage amplitudes generated on the resistive load for excitation frequencies ranging from 1494 Hz to 1498 Hz and amplitudes from $0.1 \times g$ to $2 \times g$. The excitation frequency value for which the output voltage amplitude is maximal (f_{max}) varies with the amplitude of the excitation frequency. It is caused by the nonlinearity of the mechanical structure of the generator. In fact for higher deformations (induced by high excitation levels) the rigidity of the supporting beam increases

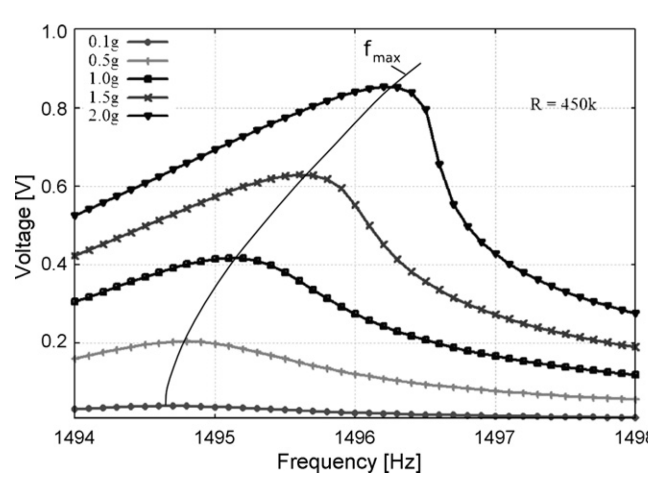

Fig. 10. Voltage amplitudes generated on a matched resistive load of 450 kΩ for different excitation frequencies and amplitudes.

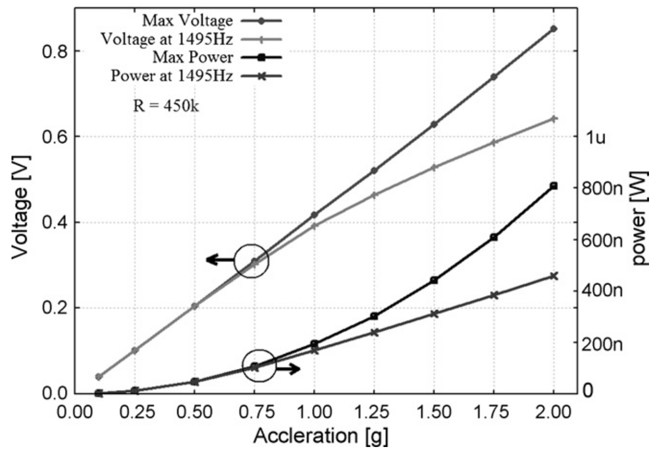

Fig. 11. Experimental voltage and power generated at resonance by one MEMS μPG on a matched resistive load vs. the input acceleration amplitude.

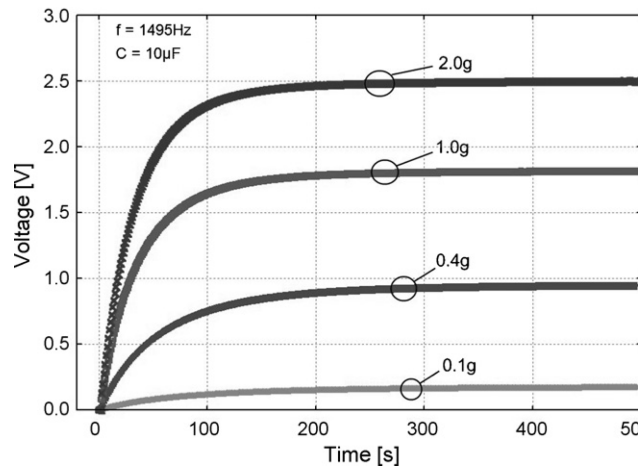

Fig. 13. Evolution of voltage in time on a 10-μF capacitor for different input acceleration levels.

and so does the resonance frequency of the structure. In a real application, in order to obtain maximum power, the excitation frequency values should therefore vary with excitation amplitude levels.

Fig. 11 presents the voltage and power obtained at resonance on a matched resistive load. Analytical models of piezoelectric micropower generators that we have developed previously [14] suggest that the output voltage at resonance should increase linearly with the excitation acceleration. Nevertheless this model does not take into account the nonlinearities of the mechanical structure. That is why in Fig. 11 we present results obtained at the linear resonance frequency of 1495 Hz as well as the maximal values obtained at frequencies varying depending on the excitation amplitude. These results show that power of 0.8 μW at 853 mV voltage amplitude can be obtained from one MEMS device at $2 \times g$ excitation.

5.2. Schottky diode rectifier

In a real application, the signal generated by the vibration scavenger must be rectified to be used to charge a storage capacitor or a battery. In the first approach we used discrete elements to assemble a simple rectification circuit. The schematic of which is shown in Fig. 12.

It is composed of two HP 5082-2835 Schottky diodes and two 6.8 nF capacitors. The circuit is capable of doubling the amplitude of the input voltage degraded by the threshold voltage of the diodes. We used this circuit to charge a 10 μF capacitor keeping the excitation frequency at 1495 Hz for all excitation levels. Fig. 13 presents the evolution of voltage in time on this load capacitor for different input acceleration levels. A maximum voltage of 2.5 V can be obtained on the capacitor with $2 \times g$ input acceleration.

From the voltage variation on the capacitor, we calculated the instantaneous power transferred to the load capacitor. It is equal to the variation of energy stored on the capacitor over time and can be calculated following equation 1. The ΔE is the difference in the energy stored in the load capacitor between t_1 and t_2, $U_{\mathrm{OUT}}(t)$ is the voltage on the load capacitor and C_{L} is the load capacitor value.

$$P_{\mathrm{inst}} = \frac{\Delta E}{\Delta t} = \frac{U_{\mathrm{OUT}}^2(t_2) - U_{\mathrm{OUT}}^2(t_1)}{t_2 - t_1} \cdot \frac{1}{2} C_{\mathrm{L}} \tag{1}$$

Fig. 14 shows the instantaneous power transferred to the load capacitor versus the voltage on this capacitor. From this figure it can be seen that the optimal point of operation varies with the

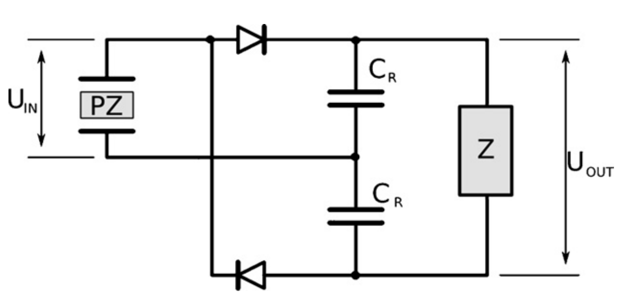

Fig. 12. Schematic of the rectifier circuit using discrete Schottky diodes.

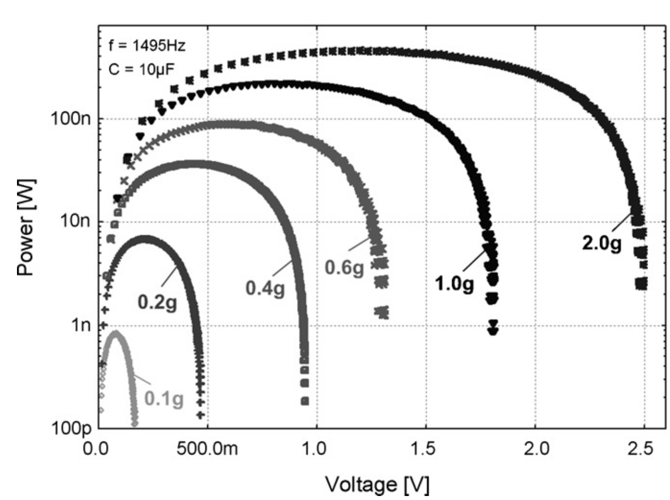

Fig. 14. Instantaneous power transferred to the 10 μF load capacitor vs. the voltage on this capacitor.

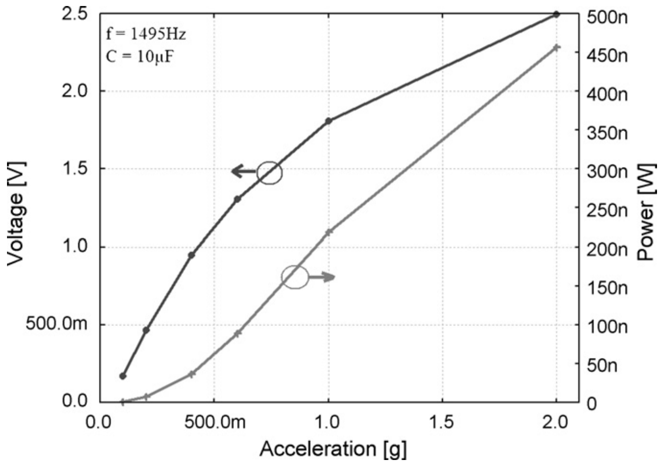

Fig. 15. Maximum voltage and maximum instantaneous power delivered to a capacitive load as a function of input acceleration amplitude.

input acceleration level. For $2 \times g$ input acceleration, maximum power of over 0.45 μW can be transferred to a capacitive load at 1.5 V, and powers of up to 0.1 μW at voltages as high as 2.3 V.

Fig. 15 presents the maximum values of the voltage that can be obtained on a capacitive load of 10 μF and the maximum value of instantaneous power transferred to this load versus the input acceleration value. As expected, the maximum voltage values do not increase linearly with the input acceleration amplitude. It is due to the fact that during the experiment, the excitation frequency was always equal to 1495 Hz for every excitation level, while the frequency for which the output voltage is maximal varies due to the nonlinearity of the device. Maximum voltage obtained on the capacitor is higher than the voltage obtained on a matched resistive load and even higher than the open circuit voltage for the corresponding accelerations, thanks to the use of voltage doubler circuit. On the other hand, the maximum power obtained is only slightly lower than the one obtained on a matched resistive load. This difference comes from the power loss on the rectification diodes. It is important to note however

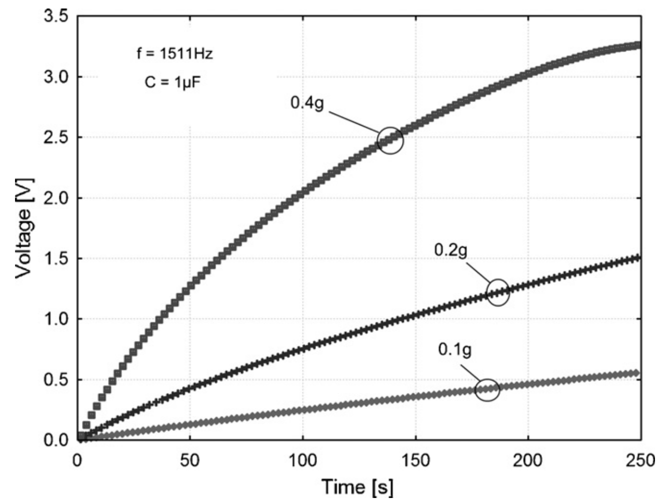

Fig. 17. Temporal evolution of voltage on a 1 μF load capacitor for different values of input acceleration amplitude.

that this maximum power can be obtained only at certain voltage levels.

5.3. System on a Package

Finally the system composed of the ASIC voltage multiplier and the MEMS generator connected on the chip level was tested. Fig. 16 presents the open circuit output voltage of the system for different input acceleration amplitudes at resonance of 1511 Hz.

These experimental results show that a 1 V output voltage can be obtained for very low excitation amplitude of about 50 mg applied on the generator. Fig. 17 presents the process of charging of a 1 μF capacitor connected to the output of our system for different input acceleration levels.

Finally Fig. 18 shows the instantaneous power with which the system is charging the 1 μF capacitor, calculated as previously with Eq. (1). It can be seen that the optimal point of operation changes with the input acceleration/voltage. For $0.4 \times g$ the optimal region is situated between 1.5 V and 3 V in which

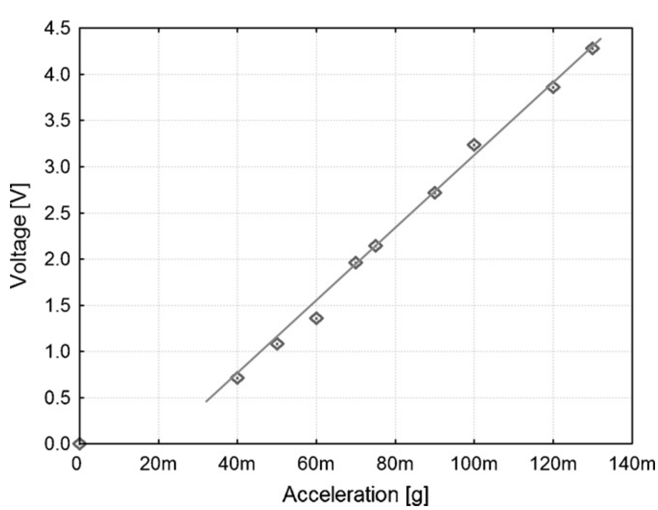

Fig. 16. Experimental open circuit voltage output of the SoP system vs. the input acceleration level.

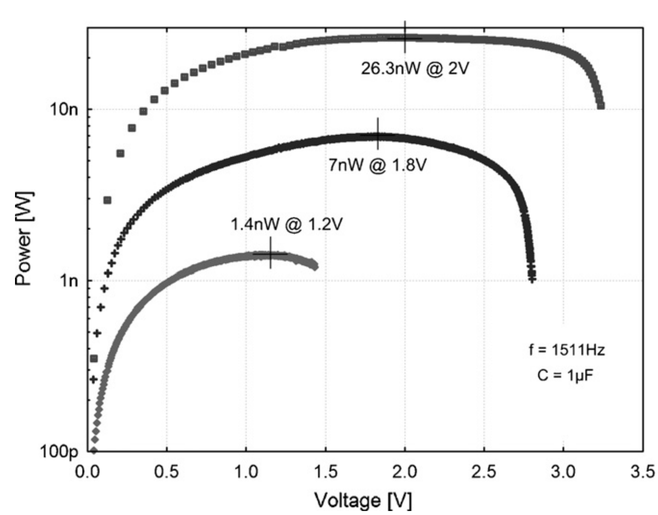

Fig. 18. Instantaneous power transferred to a 1 μF load capacitor vs. the voltage on the capacitor.

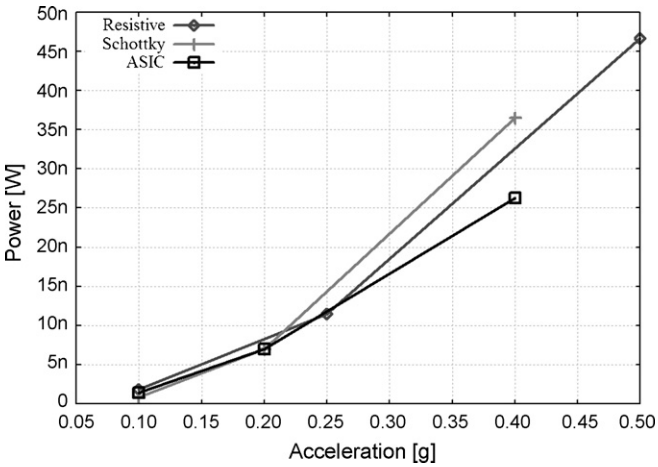

Fig. 19. Output power vs. input acceleration for three cases: matched resistive load of 450 kΩ, discrete Schottky diode rectifier with capacitive load and integrated ASIC rectifier with a capacitive load.

power of over 26 nW can be generated. The maximum output powers are similar to the ones obtained on a matched resistive load.

6. Discussion

We have presented three configurations of the energy harvesting circuits to be used with piezoelectric micropower generators. The corresponding output powers versus input acceleration amplitude are presented in Fig. 19. In the first case, the output power was obtained on a matched resistive load of 450 kΩ without rectification and for the two other cases the presented results correspond to the maximum instantaneous power transferred to a capacitive load.

It can be seen that the three options propose very similar output powers. The losses on the rectification diodes are not very important because of the fact that at low voltages (where the threshold voltage issue should be the most problematic), the currents generated by the MEMS device are very low. For low currents, the threshold voltage is also very low (Fig. 7). Furthermore, the powers presented in Fig. 19 are the maximum ones that can be obtained for optimal values of load in the resistive case and optimal operating voltage in the capacitive case. In a real application, where the operation point is not always optimal, the results would be different.

We have analyzed power consumption of a simple wireless sensor node containing a 4-bit RISC microcontroller (EM6607), a wireless transmitter (nRF24L01) as well as temperature (AD7814) and acceleration sensors (LIS3LV02DQ). In case of a very low duty cycle operation (one action every 10 min), the average power needed for the device is equal to about 150 nW. It means that even with a very low input acceleration of $0.4 \times g$, five devices occupying a total volume of less than 5 mm^3 are sufficient to supply this power. For comparison, a best thin film lithium polymer battery of the same volume would be capable of producing this power only for less than 2 months [16]. Our solution will provide the necessary power as long as the ambient energy source exists.

7. Conclusions and future work

This paper presents an analysis of an ambient mechanical vibrations microscavenging system. Three approaches were compared, including an innovative, totally integrated system created as a System on a Package (SoP) that requires no external elements. Piezoelectric MEMS devices, manufactured using microfabrication techniques compatible with microelectronics, were used as energy transducers. Power conditioning electronics adapted for ultra low voltage input were also proposed. The experimental results show that one such system, integrated on the chip level, can produce rectified power of almost 30 nW at 3 V from acceleration of $0.4 \times g$. We have shown that a storage capacitor can be efficiently charged even in case of very low input acceleration levels. It proves the usefulness of the proposed device as an ecological and very long lasting alternative for powering wireless sensor nodes.

The future work consists in using other piezoelectric materials and improving the effectiveness of the AC/DC and DC/DC converters for charging microbatteries or supercapacitors.

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Biographies

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