Design and Implementation of Interface Circuits Intended for Printed Piezoelectric Micropower Harvesters on Flexible Substrates

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Abstract. Interface circuits with low power dissipation is proposed and implemented, which is useful for efficient AC/DC voltage conversion of thin-film piezoelectric micro-power stack mounted harvesters. The focus is on low-power (< 1 µW) elements consisting of printed PVDF-TrFe piezoelectric polymer on BaSrTiO₃ coated flexible substrate with total thickness of the stack 3.1 µm. Using silver thin films as bottom and top electrodes, the samples exhibited stable piezoelectric rms voltage between 200 mV and 400 mV produced from functional area of ~1.5 cm² when stimulates it with sinewave vibration with frequency of 50 Hz and intensity equivalent to mass loading between 1–80 g. The current registered from a single harvesting element is not greater than 1 µA. For this type of harvesters two power processing circuits intended are designed and built. The first circuit is a voltage doubler, for which the rectified output voltage is approximately equal to twice of the amplitude of the input voltage. The second circuit is a voltage quadrupler; as compared to the first one it provides higher voltage for charging a small and thin-size chip supercapacitor connected to the output port, but due to diodes voltage drops a smaller value of the energy efficiency can be obtained. For the implementation of the electronic circuits, low-power Schottky diodes with a forward voltage below 0.1 V at current up to 0.1 mA are chosen. An experimental study to verify the efficiency of the proposed circuits is performed with laboratory made thin-film piezoelectric harvesters.

1. Introduction
Mechanical-to-electrical energy conversion for application as alternative energy source is a process by which elastic wave causes deformation in some materials resulting in dipole formations, thus converted to electrical energy due to direct piezoelectric effect. As the sources of mechanical waves could strongly vary from human motion, cars or industrial machines vibrations, to weather conditions (wind flow, water fall) and etc., the application of such elements are in the bioelectronics, automotive and industrial electronics for supplying low-power and portable consumers [1]. The piezoelectric energy harvesting (PEH) elements have to be sensitive, effective, but in the same time small sized and light weighting, especially in the field of health care applications. This is achieved by using thin films of piezoelectric materials, which is in opposition with the required high efficiency that could be achieved from small volume of material. One of the issues toward commercialization of such battery-less and portable devices is the inability of the piezoelectric coatings to produce electrical power beyond few micro-Watts. Additionally, it is preferable to grow the entire element on flexible substrate.
for greater compactness. The implementation of materials with naturally high piezoelectric coefficients partially solves the above highlighted problems [2]. They are usually oxide based in composition (BaTiO₃, PbZrTiO₃, KNbO₃ etc.) and are characterized with high Young modulus and brittleness [3]. Introduction of material with elastic coefficient closer to that of the flexible substrate neutralizes the stress that the oxide material experiences and would increase the stability of the generated signal due to the enhanced mechanical stability of the energy converting coating. Very often the piezoelectric polymers can successfully serve like such kind of buffer material [4].

The flexible harvesting elements reported in this paper are made from piezoelectric polymer poly(vinylidene fluoride-co-trifluoroethylene) P(VDF-TrFE) characterized with low Young modulus of 0.61 GPa [5] favourable for durability at bending and twisting substrates and piezoelectric ceramic barium strontium titanate (BaSrTiO₃ or BST) with high piezoelectric coefficient of 33.4 pC/N [6] preferable for strong piezoelectric response provoked even by weak dynamic load. The combination of both materials results in enhanced piezoelectric voltage generating abilities and long term stability of the signal at multiple repeating bends or twists.

For converting the mechanical strain energy into electricity by a PEH, the basic ac/dc converter is as a diode rectifier is connected to a rechargeable battery or a supercapacitor. The main disadvantage of this type of interface circuits is that as a result of the voltage amplitude fluctuations, generated by the PEH, the power that is extracted can be significantly reduced [7]. For batteries and supercapacitors, a fixed value of the voltage is required. For the last few years the analysis of the literature resources shows a wide variety of power energy-harvesting circuits, based on active electronic components [8-12]. In this work the focus is on the interface circuits in [8], [10] and [12] that operate at an input voltage with rms value less than 1 V and the output power is below 10 μW, because the fabricated printed PEHs on flexible substrate produce an ac voltage with rms value up to several hundreds of millivolts in contrast with the most wide spread processing circuits dealing with light harvesters that are able to produce dc voltage of few volts [13].

The goal of this paper is to present the design process and experimental testing of interface circuits that have to be connected between flexible P(VDF-TrFE)/BST – based piezoelectric generators and a micro supercapacitor, used as a load. Furthermore, the developed interface circuits are based on voltage doubler rectifier which has been initially presented for this type of input source in [8,13]. The proposed circuit is intended to use for micro-power (1—10 μW) thin-film PEHs and overcomes the some of the aforementioned limitations of the existing power processing circuits.

2. Structure and Preparation of Printed Piezoelectric Micropower Harvesters on Flexible Substrates

The flexible substrate was thermal resistant polyethylene naphthalate (PEN). Silver bottom and top electrodes with thickness of 450 nm were produced by thermal evaporation in vacuum at base pressure 10⁻⁶ Torr. Conventional for the MEMS technology RF sputtering was used for the BST film at argon pressure of 2.5x10⁻² Torr without additional oxidation. Sputtering voltage of 0.65 kV was set for 50 min at plasma current of 150 mA. Thus low temperature deposition process was established with plasma power of 97.5 W. The film thickness was 560 nm measured by Tencor α-step profilometer.

For the P(VDF-TrFE) ink low-cost screen printing technology was used. Particularly, the screen printing is well known and preferable additive manufacturing method, because of the simple and fast process, easy control over the deposition, as well as due to the possibility for uniform, high density coatings deposition on large area with no matter of the substrate type [14]. In addition, desired patterning of the films can be achieved in situ during the deposition without consequent photolithographic process (Fig. 1a). In this way, the proposed flexible energy harvesting is characterized with satisfactory efficiency, stability and price. After the deposition, all samples were annealed at 100°C by recommendation of the manufacturer for removing the residual solvent and initiate crystallization of the piezoelectric phase in the polymer coating. The temperature treatment is the reason for selection of BST as piezoelectric oxide from the great variety of modern lead-free piezoelectric materials, because annealing at this temperature wouldn’t cause phase transition process and properties (permittivity and loss factor) variation in the barium strontium titanate [15]. The
thickness of the fabricated polymer coating after annealing was 1.6 µm. To avoid penetration of the silver paste’s solvent deeper in the polymeric coating, the silver top electrode was not fabricated by screen printing of silver paste, but again vacuum thermal evaporation was used through shadow mask for segmenting the coating (Fig. 1b).

3. Electrical circuits and theoretical analysis
Interface circuits based on passive doubler (VD) rectifiers are proposed for converting the energy from the presented micro-power piezoelectric generators. In addition to straightening, these rectifiers also result in increased voltage by appropriately connecting a group of diodes and capacitors. Theoretically, the amplitude of the input voltage increases integer times; taking into account the voltage drops on the diodes. In order to avoid a significant decrease in the output voltage, Schottky diodes are chosen to use in the proposed circuits instead of using rectifying silicon diodes. By using a supercapacitor as an external load to the VD rectifiers, it can hold little energy at low voltage and is used as energy storage element for a short time.

3.1. Voltage doubler circuit
In Fig. 2 is a circuit diagram of a rectifier with voltage multiplication factor of two (voltage doubler circuit) is given. For this circuit, the operational principle is as follows. During the first half wave of the input signal (the polarity of the input voltage is indicated by characters without brackets) capacitor \( C_1 \) is charged through the diode \( D_1 \) to the value, equal to the amplitude of the input voltage – \( V_{c1} = V_{p0} \). In the next half wave, the input signal changes its polarity (the characters in brackets). The diode \( D_1 \) is turn off, on it is applied reverse voltage equal to the sum of the voltage of the capacitor \( C_1 \) and the input voltage. The open-circuit voltage drop (in condition that there is no load – without \( C_2 \) and the internal resistance \( r_p \) is neglected) over the piezoelectric capacitance \( C_p \) is given by [16]

\[
V_{p0} = I_p / \omega C_p .
\]  

The maximum average power extracted from a PEH occurs when the VD is one-half of the peak voltage is [7]

\[
P_{PEH,av} = V_{p0}^2 \omega C_p / 2\pi
\]  
at \( V_p = 0.5V_{p0} \) and \( P_{PEH,av} \) is the extracted power and subscript \( av \) denotes its average value.

The no load peak value of the output voltage, is found by

\[
V_B = 2I_p / \omega C_p .
\]
The internal capacitance and resistance of the PEH can be used as a part of the voltage doubler circuit, shown in Fig. 2. The PEH equivalent circuit is a simplified model that represents the dominant components of the generated current and output impedance ($Z_p = r_p \parallel C_p$) of a typical thin film low-power harvester. When a capacitor $C_2$ is connected to the VD, the output voltage becomes a rippled DC voltage, and $V_B \leq 2V_{p0}$. During this time interval, the diode $D_2$ is turn on and the capacitor $C_2$ is charged through it and through the capacitor $C_1$, which transfers a part of its charge up to a voltage equal to the sum of the amplitude of the input voltage and the voltage of $C_1$. Furthermore, the voltage drop over the diode $D_2$ limits the value of the produced piezoelectric voltage (i.e., $v_p(t) \leq V_B \leq 2V_{p0}$).

![Figure 2 Circuit diagram of voltage doubler circuit for charging supercapacitor.](image)

In comparison with the full-wave rectifiers [7, 12] the circuit in Fig. 2 has only one diode forward voltage drop in the current path at any one period of the input voltage, which increases the $V_{out}$ and further reduces the dissipation power in comparison.

### 3.2. Voltage quadrupler circuit

In Fig. 3 is a circuit diagram of a rectifier with voltage multiplication factor of four (voltage quadrupler circuit) is given. This circuit consists of four capacitors and four diodes. Moreover, this circuit can be considered as a complicated variant of the voltage doubler. Compared to it, a lower value for energy efficiency can be obtained, but a higher value of the output voltage can be achieved.

![Figure 3 Circuit diagram of voltage quadrupler circuit for charging supercapacitor.](image)

The operational principle of the circuit in Fig. 3 is analogous to the voltage doubler. In the concrete case, for the third half-wave voltage (again the polarity without brackets), the diode $D_2$ conducts and the capacitor $C_1$ is recharged to voltage $V_{C1} = V_{p0}$. The capacitor $C_3$ is charged through the diode circuit $D_3$, the capacitor $C_2$ and the capacitor $C_1$. The maximum voltage drop of capacitor $C_3$ is determined by
During this time interval the diode $D_3$ is off and the reverse voltage across it is equal to the voltage over the capacitors $C_2$ and $C_3$, which through the conductive diodes $D_1$ and $D_2$, are connected in parallel to it, i.e. $V_{D1,Rev} = 2V_{p0}$. The load capacitor $C_4$ is connected between the cathode of diode $D_4$ and one terminal of the PEH. Since the total number of the capacitors is four, the maximum value of the output rectified voltage should be four times greater than the voltage $V_{p0}$.

For both circuit variants, the capacitors are selected such that the fluctuations of the output voltage do not exceed 5% [7] of the nominal DC voltage for a specific load. To achieve greater unification and manufacturability, the capacitors can be selected with the equal capacitance, which is of average value and guarantees up to 5% ripples of the rectified voltage [17]

$$C = I_b (fU_b)^{-1} 2(k + 2) \times 10^6, \mu F \text{ at } k = 4.$$ (5)

The rectifier circuits in Fig. 2 and 3 have relatively large value of the internal resistance and a falling output characteristic, so they are used when exactly such a characteristic is required for a specified load or when the load is for a small current with constant value. By using a supercapacitor as an external load, it can hold little energy at low voltage and is used as energy storage element for a short time.

### 4. Experimental verification

Both interface circuits have been implemented on prototyping circuit boards using commercially available discrete components. The used Schottky diodes are type PMEG3002TV and 1N5817, and the capacitors are multilayer ceramic components with 1 µF capacitance. The designed circuits are intended for charging energy storage elements such as low-power thin-size supercapacitor. For the purpose of this work we used a micro supercapacitor, type XH311HU-IV07E (from Seiko Instruments) with initial capacitance more than 0.022 F and nominal capacity 12 µAh. The shaker is specially built for those specific types of PEHs and has been used to get the desired input vibrations equivalent to mass load up to 100 g and low frequency up to 50 Hz. A power signal generator ГЗ-109 is used to apply the desired ac voltage to the shaker electrical circuit, realizing cantilever type measurement. To measure the voltage drop over the supercapacitors, an Agilent 34405A 5 ½ digit multimeter and a VC820 4 ½ digital multimeter with an opto-electronic interface to personal computer are used.

To illustrate the operational principle of the voltage doubler and quadrupler circuits the transient waveforms are shown in Fig. 4 and Fig. 5. The experimental study is performed with a connected load capacitor 1 µF at the output. For the both circuits the amplitude of the input signal is 0.5 V (or 1 Vp-p) and the nominal frequency is 50 Hz. It’s obtained by sine-wave generator SFG-1013. The measured forward voltage drop over the rectifier diodes is low and approximately equal to 0.1 V. As a result, the rectified output voltage is set to 900 mV – 30% of the capacity (Fig. 4) and 1.7 V – 50% of the capacity (Fig. 5), respectively. Those results guarantee the applicability of the used electronic circuits for low voltages, generated by thin-film PEHs.

After verification of the operational principle of the two circuits, a direct charging of the 3.3 V micro supercapacitor type XH311HU-IV07E from a single PEH at two levels of excitation is performed. The obtained maximum peak-to-peak output voltage swing of the input signal, generated by single PEH, is approximately equal to 300 mVp-p and the frequency is up to 50 Hz. Fig. 6 and 7 shows the plots of an experimentally measured voltage versus charging time from a single thin-film printed piezoelectric micropower harvester by using the circuits in Fig 2 and Fig. 3. Fig. 6 shows the charge of the supercapacitor to 85 mV. As it can be seen, the charging time is approximately three hours. The charge rate of the capacitor in the initial time intervals is high and then gradually decreases to the level of the rectified output voltage. Fig. 7 also shows the charge of the supercapacitor but up to value equal to 160 mV. In this case, the charge of the supercapacitor is a little more than 6 hours, and at the initial time intervals, the charging rate is again with higher value.
**Figure 4.** Measured transient waveforms for input and output nodes in the voltage doubler at 1 µF load capacitor.  
Horizontal scale is 10ms/div  
Vertical scale is 500mV/div – Channel 1 and 2

**Figure 5.** Measured transient waveforms for input and output nodes in the voltage quadrupler at 1 µF load capacitor.  
Horizontal scale is 10ms/div  
Vertical scale is 500mV/div – Channel 1 and 1V/div – Channel 2

**Figure 6.** Experimentally measured voltage from single PEH on a micro supercapacitor type XH311HU for voltage doubler circuit.  
**Figure 7.** Experimentally measured voltage from single PEH on a micro supercapacitor type XH311HU for voltage quadrupler circuit.

5. **Conclusion**  
In this paper, the behaviour of two conversion circuits based on the voltage doubler rectifier is evaluated for charging micro supercapacitors. The developed rectifier circuits are intended for working with mounted in stack thin-film PEHs, consisting of printed PVDF-TrFE piezoelectric polymer on BaSrTiO$_3$ coated flexible substrate with total films thickness of the piezoelectric coatings in single element equal to 3.1 µm and active piezotransducing area equal to 1.5 cm$^2$. The conversion circuit of voltage doubler rectifier has only one diode forward voltage drop in the current path at any one period of the input voltage, which provides slightly higher value of the energy efficiency. Its convenient for low power single PEHs. For the voltage quadrupler circuit lower value for energy efficiency can be obtained, but a higher value of the output voltage can be achieved. The voltage quadrupler can be used for mounted in stack thin-film PEHs.

The measurement results show the contribution of single PEH from the stack for charging supercapacitors. Due to the high internal impedance of the synthesized PEHs, conventional active full-wave synchronous rectifiers do not provide efficient power conversion. The maximum average power extracted from the single PEH is up to 1 µW. To overcome the low output voltage, Schottky diodes with a small forward voltage (≈ 100 mV) are chosen.
6. References

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