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Electrical Characterization of a Unimorph Vibration Energy Harvester with Al/AlN/Al Structure Realized by Magnetron Sputtering

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Abstract: In this work, the realization of a unimorph vibration energy harvester with an Al/AlN/Al structure by magnetron sputtering is proposed. Starting from an Al substrate, the device with an Al/AlN/Al structure was obtained by using a magnetron sputtering in two different operative conditions. The realized energy harvester was investigated in the unimorph bender set-up. The electrical characterization was performed by estimation of the AlN d_{31} piezoelectric coefficient and measurements of the output power. The estimated absolute value of d_{31} was 0.48 pC/N and the maximum output power was about 17 μ W with 9.81 m/s² (rms value) excitation acceleration.

Keywords: aluminum; aluminum nitride; magnetron sputtering; piezoelectric; vibration energy harvester



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1. Introduction

Vibration based energy harvesting is an important field of research for the development of self-powered wireless sensor network nodes and portable devices. The development of self-powered solutions without the need for batteries is of interest for many applications [1].

For achieving this result, ultra-low power electronics is important in order to reduce the power requirement as much as possible, and energy harvesting from the environment is a way to power wireless sensors and portable devices. Regarding the power range of interest for applications, ultra-low power electronics has an input power that is in the range from microwatt to milliwatt [2,3]. Regarding the energy-harvesting technique, there are different types of vibration-based energy harvesters. There are three main methods: electromagnetic, electrostatic, and piezoelectric [1,4]. In particular, piezoelectric energy harvesting is an easy solution for the conversion of mechanical vibration energy into electrical energy through the piezoelectric effect [1,4–6]. Vibration piezoelectric energy harvesters with an obtained output power that is within the input power range of ultra-low power electronics are reported in the literature [7]. Different piezoelectric materials have been studied for energy-harvesting applications, and among them, lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF) are well known solutions [8]. Another solution suitable for energy-harvesting applications is aluminum nitride (AlN), which has interesting properties such as a favorable figure of merit and low toxicity (it is a lead-free material) [7,9].

An important aspect for applications is the growth of AlN films oriented along the c-axis. Different methods have been investigated for the realization of high-quality AlN films, and among them, the sputtering technique is a well-known method, and aluminum (Al) is among the different studied substrates [7,9–11].

Power output values for AlN-based devices are reported in the literature in the range of tens/hundreds of microwatts, even if a comparison of devices is not immediate, as many factors such as design and operating conditions affect the harvester performances [7,9,12].

A case of interest is the Al/AlN/Al structure [11]. After the realization of AlN/Al structure, the second electrode in Al can be obtained by different techniques such as thermal evaporation [11], ion-beam assisted deposition [13], and magnetron sputtering [14].

A preliminary study of AlN film deposited on Al substrate by pulsed-reactive magnetron sputtering has already been presented in a previous paper [15]. Thick films with thickness of 20–30 μm were obtained, and the AlN thick films characterization was performed. The second electrode was realized by silver conductive paint, obtaining the Ag/AlN/Al structure.

In this work, the realization of a unimorph energy harvester with an Al/AlN/Al structure is reported. This structure has Al for both electrodes and was obtained as follows.

We started from an Al substrate and an Al target, and the AlN deposition on Al was made by operating the magnetron sputtering as already reported in a previous paper [15]. Then, as part of the activity of this work, the Al deposition on AlN was performed, and the used operative conditions of the magnetron sputtering for this Al deposition are reported.

The electrical characterization of the device in the unimorph bender set-up was performed. A well-known electromechanical model of the cantilever beam configuration for energy-harvesting applications uses the Euler–Bernoulli beam theory [16,17]. A simple solution, even if it is an approximate solution, is given by the use of only the first natural frequency of the model, for the case of excitation around a natural frequency of the bender [16]. In this paper, the analytical solution in the simple form of the first natural frequency of the model is used for the fitting of the experimental data in order to obtain the estimation of the d_{31} AlN transverse piezoelectric coefficient. The experimental set-up, the analytical solution of the model, and the corresponding data interpolation function are described in Section 2. The value of the AlN piezoelectric parameter d_{31} was estimated and the output power was measured. These results are presented in Section 3 and are discussed in Section 4. Finally, the main conclusions are reported.

2. Materials and Methods

2.1. Magnetron Sputtering System

A magnetron sputtering system was used, with a stainless steel chamber that is almost parallelepiped in shape (about $457 \times 457 \times 612 \text{ mm}^3$). It is equipped with a large door ($527 \times 680 \text{ mm}^2$) that allows for an easy insertion or extraction of substrates and samples. Figure 1 shows the inner view of the chamber, where a single cathode with a circular/planar (six inches diameter) aluminum 99.99% target is present. Over the target, there is a shutter, rotatable from the outside of the chamber, and over it, there is a rotatable structure for positioning the substrates over the target.

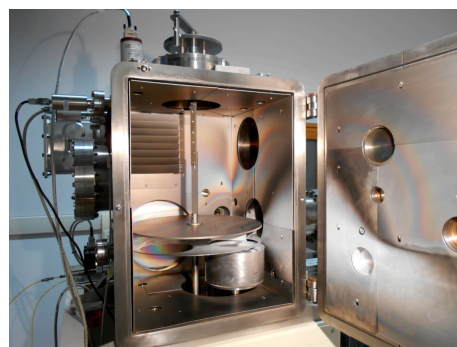


Figure 1. Inner view of the magnetron sputtering stainless steel chamber.

For the refrigeration of the cathode, a water-cooled closed circuit was used. A safety system with interlocks against mistakes in the system operation is present. Argon and nitrogen gases were used in the magnetron sputtering operation.

The substrate was placed at about 6 cm above the target.

A pulsed-power (TruPlasma DC 4001, Huettinger, Zielonka, Poland; 1 kW maximum output power) operating with a repetition frequency of 50 kHz (with a duty cycle of 90%) was used.

The base vacuum pressure of the sputtering chamber was always less than 0.1 mPa. A preliminary pre-sputtering in Argon was performed before each deposition.

The realization of the Al/AlN/Al structure was carried out in two steps. The first step was to use Al as substrate (commercial AISI 1050A aluminum) and, after smoothing its surface, to obtain the growth of the AlN film on the Al substrate by pulsed-magnetron reactive sputtering. This part was studied in a preliminary research activity [15]. The second step was to mask the AlN/Al structure, and, then, by pulsed-magnetron sputtering, the Al deposition was performed.

2.2. Unimorph Vibration Energy Harvesting

The Al/AlN/Al structure has the substrate in Al (with parallelepiped geometry and a measured thickness value of 1.87 mm), an AlN thick film as the piezoelectric material, and an Al thin film as the second electrode. This structure can be modelled as a parallel plate capacitor, with one plate (deposited Al) having a smaller area than the other (Al substrate).

The sample made with this structure was used as a unimorph-type energy harvester. In Figure 2, a sketch of the unimorph type cantilever is reported: indicated along the length of the beam are the distances from the clamp of the initial and final position (x_1 and x_2 respectively) of the Al film (top electrode), and the length L of the cantilever beam.

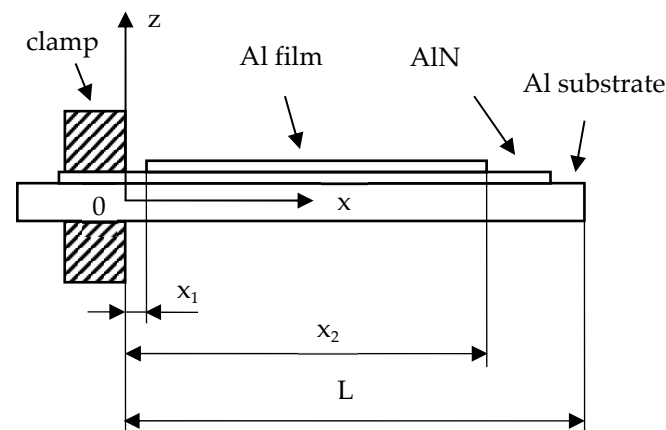


Figure 2. Sketch of the unimorph type cantilever.

The sample was mounted on an electrodynamic shaker (model 2007E of the Modal Shop Inc., Cincinnati, OH, USA) and clamped as a cantilever beam. The shaker was driven by a signal voltage generator and a power amplifier. The frequency was varied, and the excitation acceleration was measured by an accelerometer placed on the clamp of the cantilever beam. The accelerometer output was connected to a signal conditioner and finally to an oscilloscope input channel. On another input channel of the oscilloscope the sample output voltage was visualized.

The unimorph harvester model with harmonic excitation proposed in the literature was used for the analysis of the frequency response of the voltage output [16]. The cantilever beam was assumed with no base rotation, and only the first natural frequency was considered.

2.2.1. Open Circuit Voltage

The open circuit condition is obtained when $R_L \gg \frac{1}{\omega C_p}$, where R_L is the load resistance, C_p is the capacitance of the sample, and ω is the angular frequency [16]. In the case of open circuit, the model shows that the root mean square (rms) value of the output voltage (V_0) is as follows [15]:

$$V_0 = E \frac{0.783 \sqrt{m L} \frac{|\chi_1|}{C_p}}{\sqrt{\left(\frac{\chi_1^2}{C_p^2} + \omega_1^2 - \omega^2\right)^2 + (2\zeta_1 \omega_1 \omega)^2}}, \quad (1)$$

where E is the rms value of the excitation acceleration, ω_1 is the first natural angular frequency, ζ_1 is the damping ratio for the first mode, m is the mass per unit length of the beam, L is the length of the beam, and χ_1 is the coupling term for the first mode [15,16].

According to (1), a data fit was carried out by the following interpolation function:

$$V_0 = m_1 + \frac{m_2}{\sqrt{(\omega^2 - m_3^2)^2 + (\omega m_4)^2}}, \quad (2)$$

with m_1 in V, m_2 in V/s², m_3 in s⁻¹, and m_4 in s⁻¹.

With respect to Equation (1), in Equation (2), the m_1 term was added in the data fit to account for voltage offset in the measured signal. Therefore, from the experimental data V_0 and E , and the data fit given by Equation (2), the m_2 value was obtained. Comparing Equation (2) to Equation (1), it results in the following:

$$m_2 = 0.783 E \sqrt{m L} \frac{|\chi_1|}{C_p}. \quad (3)$$

Moreover, for the unimorph harvester, the following relation for χ_1 was used [15]:

$$\chi_1 = -d_{31} Y_p b_p \frac{h_s}{2} \frac{d\Phi_1(x)}{dx} \Big|_{x=x_1}^{x=x_2}, \quad (4)$$

where Y_p is the Young's modulus of the piezoelectric material, d_{31} is the piezoelectric constant, b_p is the width of the piezoelectric material, and h_s is the thickness of the Al substrate. The function $\Phi_1(x)$ in (4) is defined as follows [17]:

$$\Phi_1(x) = \frac{1}{\sqrt{mL}} \left\{ \cosh\left(\frac{\lambda_1}{L}x\right) - \cos\left(\frac{\lambda_1}{L}x\right) - \sigma_1 \left[\sinh\left(\frac{\lambda_1}{L}x\right) - \sin\left(\frac{\lambda_1}{L}x\right) \right] \right\}, \quad (5)$$

with $\lambda_1 = 1.8751$, and $\sigma_1 = 0.7341$ [17].

With the realized sample, the following values were used. The measured values were $x_1 = 5$ mm, $x_2 = 72$ mm, $b_p = 18.5$ mm, $L = 95$ mm, $h_s = 1.87$ mm, and b_s (width of the Al substrate) = 30 mm. Moreover, the aluminum mass density value was taken, $\rho_{Al} = 2700$ kg/m³, and AlN Young's modulus value was taken, $Y_p = 345$ GPa [18]. The mass per unit length of the beam was calculated: $m = \rho_{Al} b_s h_s = 151.5 \times 10^{-3}$ kg/m.

Finally, all the experimental data were obtained with $E = 9.81$ m/s².

From Equations (3)–(5), and using the values indicated above, the absolute value of the piezoelectric coefficient results in the following:

$$|d_{31}| = \frac{C_p m_2}{k} \quad (6)$$

with $k \approx 1.13 \times 10^9$ N/s², C_p in F, and d_{31} in C/N.

The capacitance C_p was measured at the first natural frequency by an LCR meter (LCR-6300, Good Will Instrument Co., Taipei, Taiwan). Moreover, as already reported, from the data fit given by Equation (2), the m_2 value was obtained.

By using Equation (6), the estimate of the absolute value of d_{31} was obtained.

2.2.2. Output Power

In Figure 3, the energy harvester is represented as an equivalent electrical circuit consisting of an AC current source $j(t)$ in parallel with a capacitor (sample capacitance C_p), and the electrical load is represented as a resistor with resistance R_L [12,16].

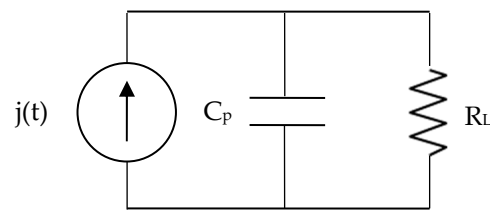


Figure 3. Energy harvester electrical equivalent circuit: sinusoidal current source in parallel with a capacitor C_p . The load is placed in parallel to them (resistor R_L).

The maximum output power is obtained with a resistance value [12]:

$$R_L = \frac{1}{\omega C_p} \quad (7)$$

The output power:

$$P_L = \frac{V_L^2}{R_L} \quad (8)$$

where V_L is the rms value of the output voltage measured on the load resistance. The voltage was measured by using an oscilloscope (Yokogawa DL9140, Tokyo, Japan) with a voltage probe.

3. Results

3.1. Sample Realization with Al/AlN/Al Structure

The sample realization was made in two steps: the AlN/Al structure was the first step and then, after masking, the Al deposition.

As a first step, the AlN/Al structure was made following the operative conditions of one of the cases analyzed in the preliminary study [15]. The AlN thick film was made by pulsed-magnetron reactive sputtering, with the operative pressure set at 0.3 Pa. Argon and nitrogen flow rates were set by a mass flow controller for each gas, and the total value (i.e., the sum of nitrogen and argon flow rates) was kept equal to 25 sccm. The nitrogen concentration, i.e., the ratio between the nitrogen flow rate and the 25 sccm total flow rate, was set at 0.4. The output power value of the pulsed-DC power supply used was set equal to 150 W. The process lasted 50 h. As reported in [15], with these operative conditions, the resulting film thickness was $h_{\text{AlN}} = 28.7 \mu\text{m}$. This value was assumed in the present work as the same operating conditions were used.

As a second step, new with respect to the preliminary analysis, the obtained AlN/Al structure was masked in air by using Kapton tape in such a way that an area of $67 \times 18.5 \text{ mm}^2$ of the AlN upper surface was left uncovered for the Al deposition. The Al deposition was made by using the magnetron sputtering system operated only with argon gas with flow rate of 25 sccm and pressure set at 2 Pa. The output power value (of the pulsed power supply) was set at 100 W. The process lasted 3 h. In this way, a parallel plate capacitor structure was obtained.

In Table 1, the magnetron sputtering main operative conditions for AlN deposition on Al substrate and Al deposition on AlN/Al structure are reported.

Table 1. Magnetron sputtering main operative conditions used for AlN deposition on Al substrate and Al deposition on AlN/Al structure.

Deposition	Power (W)	Pressure (Pa)	Operating Time (h)	Ar Flow Rate (sccm)	N ₂ Flow Rate (sccm)
AlN on Al substrate	150	0.3	50	15	10
Al on AlN/Al structure	100	2	3	25	0

A copper tape with conductive adhesive (3M 1181 tape) was used to extend the electrode realized by Al deposition. Moreover, the copper tape was also placed on the Al substrate to obtain an easy connection. Kapton tape (Tesa 51408, Tesa, Norderstedt, Germany) was used for electrical insulation. The realized sample is shown in Figure 4.

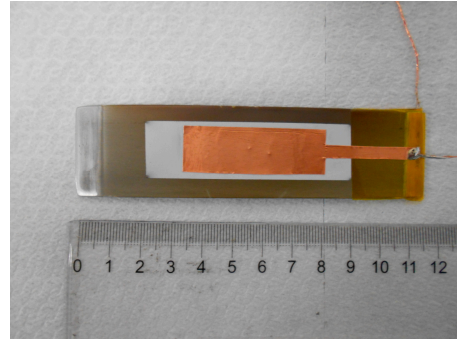


Figure 4. Sample used as unimorph energy harvester.

3.2. Vibration Unimorph Energy Harvester

The sample with Al/AlN/Al structure was clamped near one end to make a cantilever configuration. The sample was mounted on top of the electrodynamic shaker, which was driven by a signal voltage generator and a power amplifier, and the accelerometer was placed on the clamp. The sample output voltage and the electrical signal related to the excitation acceleration were visualized by an oscilloscope. In Figure 5, the experimental set-up is shown.

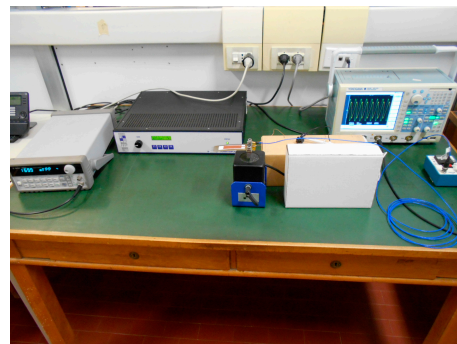


Figure 5. Vibration unimorph energy harvester experimental set-up.

The electrical load, consisting of the voltage probe connected to the oscilloscope, was $R_L = 10 \text{ M}\Omega$. The output voltage was measured varying ω in the range of 450–1600 rad/s. The maximum (rms value) of the output voltage was measured at $f = 159.4 \text{ Hz}$ (the same rms value was measured at $f = 159.3 \text{ Hz}$ and $f = 159.5 \text{ Hz}$). The capacitance value, measured at the frequencies 159.3 Hz, 159.4 Hz, and 159.5 Hz with an LCR meter, was $C_p = 3.88 \text{ nF}$. With these values of ω , R_L , and C_p , the open circuit condition $R_L \gg \frac{1}{\omega C_p}$ was satisfied.

In Figure 6 the experimental values (full circles) of the open circuit output voltage V_0 (rms value) versus angular frequency are reported. As already mentioned, the experimental data were obtained with the rms value of the excitation acceleration equal to 9.81 m/s^2 . The open circuit output voltage, starting from low frequency, at first increases with frequency as the mechanical structure approaches the resonance vibration frequency. After the mechanical resonance, the output voltage decreases.

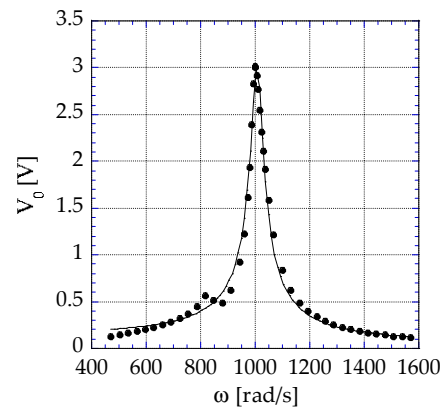


Figure 6. Open circuit output voltage V_0 (rms value) vs. angular frequency: experimental values (full circles) and numerical fit (continuous line).

By using Equation (2), the numerical fit of the open circuit output voltage experimental values was carried out (continuous line in Figure 6). The values of m_1 , m_2 , m_3 , and m_4 parameters resulting from the data interpolation are reported in Table 2. The analysis of these values is reported in the Discussion.

Table 2. Values of the parameters of the interpolation function fitted from the experimental data shown in Figure 6.

m_1 [V]	m_2 [V/s ²]	m_3 [s ^{−1}]	m_4 [s ^{−1}]
0.0265	1.3966×10^5	1006.6	46.729

Then, the frequency was set at $f = 159.4$ Hz, and twelve different values of load resistance R_L were used in the range 100 k Ω –10 M Ω . For each value of load resistance, the corresponding output voltage V_L was measured. The output power was calculated by using Equation (8), and the obtained results are reported in Figure 7. Among the results, the maximum value was $P_L \approx 17$ μ W with $R_L = 259$ k Ω .

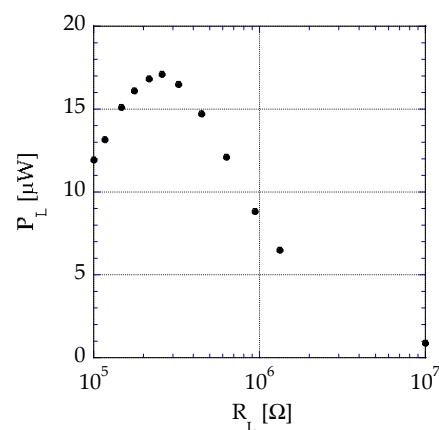


Figure 7. Output power versus load resistance (at $f = 159.4$ Hz, and excitation acceleration rms value equal to 9.81 m/s²).

4. Discussion

The capacitance of the device with an Al/AlN/Al structure was $C_p = 3.88$ nF measured at 159.4 Hz. For the discussion of this C_p value, the data reported in [15] relative to a deposition of AlN on Al substrate obtained in the past by magnetron sputtering, with the same operative conditions set for this research work, i.e., $h_{\text{AlN}} = 28.7$ μ m, and a value of AlN relative permittivity $\epsilon_{33r} \approx 9$, are used for the evaluation. The model of parallel plate capacitor is considered. From the relation:

$$C_P = \varepsilon_0 \varepsilon_{33r} A / h_{\text{AlN}} \quad (9)$$

with $\varepsilon_0 \approx 8.854 \times 10^{-12}$ F/m, $A = 67 \times 18.5 \text{ mm}^2$ (the area of the deposited aluminum in this work), and, as above mentioned, with $h_{\text{AlN}} = 28.7 \text{ }\mu\text{m}$, $\varepsilon_{33r} \approx 9$, a capacitance value of about 3.4 nF results, which differs less than 15% from the measured value.

The values of the parameters of the interpolation function fitted from the experimental data shown in Figure 6 and reported in Table 2 are discussed.

The m_1 term, as already introduced, accounts for the voltage offset in the measured signal.

The m_2 term gives the estimation of the d_{31} AlN piezoelectric coefficient. From the value $m_2 = 1.3966 \times 10^5 \text{ V/s}^2$ and by using Equation (6), an absolute value of d_{31} of 0.48 pC/m resulted, which is very close to the value of 0.52 pC/N obtained with the Ag/AlN/Al structure reported in a previous paper [15]. This value, even if it is not so high, is comparable with the experimental data obtained on AlN films indicated in the literature [19].

For the discussion of the m_3 value, as a preliminary analysis, from Equation (3), it results with $|\chi_1| = \frac{C_p m_2}{0.783 E \sqrt{m L}}$ and therefore it can be calculated by using the values reported above, i.e., $C_p = 3.88 \text{ nF}$, $m_2 = 1.3966 \times 10^5 \text{ V/s}^2$, $E = 9.81 \text{ m/s}^2$, $m = 151.5 \times 10^{-3} \text{ kg/m}$, and $L = 95 \text{ mm}$. The term $\frac{\lambda_1^2}{C_p}$ in Equation (1) can also be calculated: $\frac{\lambda_1^2}{C_p} \approx 89.1 \text{ s}^{-2}$. By comparing between Equations (1) and (2), it results the relation $m_3^2 = \frac{\lambda_1^2}{C_p} + \omega_1^2$, and now ω_1 can be obtained. From the values, it results with $\omega_1 \approx m_3 = 1066.6 \text{ rad/s}$. From the theory, the value of the first natural angular frequency is given by the following relation [16]:

$$\omega_1 = \lambda_1^2 \sqrt{\frac{Y I}{m L^4}} \quad (10)$$

where the product YI is the flexural stiffness of the beam. For the unimorph cantilever beam of this paper, in first approximation, the flexural stiffness is due to the Al substrate having a rectangular cross-section (thickness value h_s , width value b_s). Therefore, Y is the aluminum Young's modulus, and I , the area moment of inertia of a rectangular cross-section, is equal to $\frac{b_s h_s^3}{12}$. The Al Young's modulus value was taken as $Y = 70 \text{ GPa}$ [20]. From Equation (9), it results in a value of the first natural angular frequency, $\omega_1 \approx 1071 \text{ rad/s}$. This value is in good agreement with the value of 1066.6 rad/s obtained for the m_3 parameter.

Moreover, comparing Equations (1) and (2) yields $m_4 = 2\zeta_1 \omega_1$. From this relation, the damping ratio for the first mode results in $\zeta_1 = \frac{m_4}{2\omega_1}$. With $m_3 \approx \omega_1$, it results in $\zeta_1 \approx \frac{m_4}{2m_3} \approx 0.023$.

The harvester output power was measured by using, as resistive loads, commercial discrete load resistance values and the voltage probe connected to the oscilloscope. The output power presents its maximum, among the analyzed cases (Figure 7), for $R_L = 259 \text{ k}\Omega$. This is in very good agreement with Equation (7), from which, with $f = 159.4 \text{ Hz}$ and $C_p = 3.88 \text{ nF}$, results in $R_L = 257 \text{ k}\Omega$.

It can be observed that the measured output power value of 17 μW is within the input power range of ultra-low power electronics.

5. Conclusions

In this paper, an electrical characterization of an unimorph energy harvester with Al/AlN/Al structure realized by magnetron sputtering is presented. This structure was obtained by operating a magnetron sputtering in two different operative conditions. An output power $P_L \approx 17 \text{ }\mu\text{W}$ with $R_L = 259 \text{ k}\Omega$ at 9.81 m/s^2 (rms value) of excitation acceleration was measured, which is a value of interest for ultra-low power electronics. For the estimation of the AlN d_{31} piezoelectric coefficient, a simple solution was adopted. The Euler–Bernoulli beam theory was used for the unimorph harvester model with harmonic excitation, and only the first natural frequency was considered. The output voltage analytical relation in the open circuit condition was written in the form of an interpolation

function with four parameters for the data fit. From one of these parameters, the absolute value of the AlN d_{31} piezoelectric coefficient was estimated to be 0.48 pC/N.

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References

1. Wei, C.; Jing, X. A comprehensive review on vibration energy harvesting: Modelling and realization. *Renew. Sustain. Energy Rev.* **2017**, *74*, 1–18. [\[CrossRef\]](#)
2. Pop-Vadean, A.; Pop, P.P.; Barz, C.; Chiver, O. Applications of energy harvesting for ultralow power technology. In Proceedings of the International Conference on Applied Sciences 2014 (ICAS2014), Hunedoara, Romania, 2–4 October 2014.
3. Galea, F.; Casha, O.; Grech, I.; Gatt, E.; Micallef, J. An ultra low power CMOS MPPT power conditioning circuit for energy harvesting. In Proceedings of the 2020 IEEE International Symposium on Circuits and Systems (ISCAS), Seville, Spain, 12–14 October 2020.
4. Toprak, A.; Tigli, O. Piezoelectric energy harvesting: State-of-the-art and challenges. *Appl. Phys. Rev.* **2014**, *1*, 031104. [\[CrossRef\]](#)
5. Sezer, N.; Koc, M. A comprehensive review on the state-of-the-art of piezoelectric energy harvesting. *Nano Energy* **2021**, *80*, 105567. [\[CrossRef\]](#)
6. Pradeesh, E.L.; Udhayakumar, S.; Vasundhara, M.G.; Kalavathi, G.K. A review on piezoelectric energy harvesting. *Microsyst. Technol.* **2022**, *28*, 1797–1830. [\[CrossRef\]](#)
7. Fei, C.; Liu, X.; Zhu, B.; Li, D.; Yang, X.; Yang, Y.; Zhou, Q. AlN piezoelectric thin films for energy harvesting and acoustic devices. *Nano Energy* **2018**, *51*, 146–161. [\[CrossRef\]](#)
8. Vatansever, D.; Hadimani, R.L.; Shah, T.; Siores, E. An investigation of energy harvesting from renewable sources with PVDF and PZT. *Smart Mater. Struct.* **2011**, *20*, 055019. [\[CrossRef\]](#)
9. Haider, S.T.; Shah, M.A.; Lee, D.-G.; Hur, S. A review of the recent applications of aluminum nitride-based piezoelectric devices. *IEEE Access* **2023**, *11*, 58779–58795. [\[CrossRef\]](#)
10. Iqbal, A.; Mohd-Yasin, F. Reactive sputtering of aluminum nitride (002) thin films for piezoelectric applications: A review. *Sensors* **2018**, *18*, 1797. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Song, X.; Fu, R.; He, H. Frequency effects on the dielectric properties of AlN film deposited by radio frequency reactive magnetron sputtering. *Microelectron. Eng.* **2009**, *86*, 2217–2221. [\[CrossRef\]](#)
12. Elfrink, R.; Kamel, T.M.; Goedbloed, M.; Matova, S.; Hohlfeld, D.; van Andel, Y.; van Schaijk, R. Vibration energy harvesting with aluminum nitride-based piezoelectric devices. *J. Micromech. Microeng.* **2009**, *19*, 094005. [\[CrossRef\]](#)
13. Gablech, I.; Klempa, J.; Pekarek, J.; Vyroubal, P.; Hrabina, J.; Hola, M.; Kunz, J.; Brodsky, J.; Neuzil, P. Simple and efficient AlN-based piezoelectric energy harvesters. *Micromachines* **2020**, *11*, 143. [\[CrossRef\]](#) [\[PubMed\]](#)
14. He, X.; Wen, Q.; Lu, Z.; Shang, Z.; Wen, Z. A micro-electromechanical systems based vibration energy harvester with aluminum nitride piezoelectric thin film deposited by pulsed direct-current magnetron sputtering. *Appl. Energ.* **2018**, *228*, 881–890. [\[CrossRef\]](#)
15. Desideri, D.; Bernardo, E.; Corso, A.J.; Moro, F.; Pelizzo, M.G. Electrical properties of aluminum nitride thick films magnetron sputtered on aluminum substrates. *Materials* **2022**, *15*, 2090. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Erturk, A.; Inman, D.J. A distributed parameter electromechanical model for cantilevered piezoelectric energy harvesters. *J. Vib. Acoust.* **2008**, *130*, 041002. [\[CrossRef\]](#)
17. Erturk, A.; Inman, D.J. On mechanical modeling of cantilevered piezoelectric vibration energy harvesters. *J. Intell. Mater. Syst. Struct.* **2008**, *19*, 1311–1325. [\[CrossRef\]](#)
18. Shackelford, J.F.; Alexander, W. *CRC Materials Science and Engineering Handbook*, 3rd ed.; CRC Press: Boca Raton, FL, USA, 2000.
19. Narayanan, K.B.; Nair, D.R.; Dasgupta, A. Extraction of d_{31} piezoelectric coefficient of AlN thin film. In Proceedings of the IEEE International Conference on Micro Electro Mechanical Systems (MEMS), Virtual, Gainesville, FL, USA, 25–29 January 2021.
20. Chinmulgund, M.; Inturi, R.B.; Barnard, J.A. Effect of Ar gas pressure on growth, structure, and mechanical properties of sputtered Ti, Al, TiAl, and Ti₃Al films. *Thin Solid Films* **1995**, *270*, 260–263. [\[CrossRef\]](#)

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