Design and simulation of the compact MEMS energy harvester based on aluminium nitride

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Abstract. A device for converting the energy of mechanical vibrations to electricity by the piezoelectric effect is presented. A main part of the transducer is a multilayer cantilever with the inertial mass at the tip. A piezoelectric layer is made of 0.5 μm thick aluminum nitride. A feature of the device is the compact lateral size of about 1 mm, which is 10 times smaller in comparison with conventional harvesters. The device is fully compatible with microelectromechanical systems (MEMS) technology. The cantilever has a natural frequency of 45-160 Hz, depending on the size and inertial mass. The transducer generates the output voltage of 0.35 V, which is high enough for rectifying by the diode bridge. The output power of 2.7 nW is relatively low due to the small size. Nevertheless, the figure of merit is higher than that for conventional AlN-based energy harvesters.

1. Introduction
Modern portable devices consume rather low power down to several tens of microwatts [1]. Typically, they are powered by a battery, which requires periodic replacement or charging. In some cases, like GPS trackers or strain gauges in buildings, these operations are inconvenient or impossible. Instead of the battery, portable devices can use energy of environmental sources, e.g. sunlight or wind. A promising and widespread energy source is mechanical vibration. Oscillation of household appliances or human body can be converted to electricity by the harvester, which is a miniature device fabricated by MEMS technology. Among several working principles [2], piezoelectric transduction is the most popular one. The piezoelectric harvester has a simple design compatible with microtechnology and demonstrates the highest efficiency [3]. It consists of a resonator with a piezo-material sandwiched between two electrodes. The commonly used material for today is lead zirconate titanate (PZT) due to high piezoelectric coefficient ~100 pm/V [4]. However, lead and its derivatives are toxic and globally considered as hazardous materials. Their usage is expected to be limited in the future, and PZT will be replaced by the lead-free materials like aluminium nitride or zinc oxide [5]. They have lower piezoelectric coefficient (2 pm/V and 5 pm/V for AlN and ZnO, respectively [6]), but they are not toxic and more suitable for MEMS technology. In recent decades, a lot of research are focused at the AlN-based transducers [2,7,8]. These devices have a footprint of about 1 cm² and generate power up to 64 μW [9]. Their disadvantage is a narrow bandwidth of 1-2 Hz, which limits the application of the harvester by a specific vibrating item. The bandwidth can be expanded by combining several resonators at a single chip, but the price is the significant increase of the harvester size. In this work, we propose a
compact piezoelectric transducer of about 1 mm in size. Performance of the device is estimated by the finite element simulation.

2. Methods
A key part of the harvester is a multilayer cantilever illustrated in figure 1. The basic layer is a 0.9 μm thick thermally grown SiO₂. A piezoelectric AlN film has a thickness of 0.5 μm. It is located between two 0.1 μm thick chromium electrodes. The length \( l \) and width \( w \) of the cantilever are in the range of 500-1000 μm and 200-1000 μm, respectively. The beam is equipped by the inertial mass (IM), which is made of 500 μm thick silicon. The bottom electrode covers the cantilever and IM. It serves as a mask for etching of SiO₂. Piezoelectric layer and upper electrode are located at the beam only, because no mechanical stress is expected above IM. The harvester is attached to the energy source. When the source moves with acceleration, the cantilever deflects from its initial position. Mechanical stress polarizes AlN, which results in a voltage between the electrodes and a current in the external circuit. The current is rectified by diodes and the electric energy is accumulated in a supercapacitor.

Two operating regimes of the harvester are considered. In the static regime, the acceleration is constant and equals to \( g = 9.8 \text{ m/s}^2 \). The deflection of the cantilever tip, output voltage and natural frequency are studied. In the vibrating regime, the acceleration oscillates with time as \( a = a_0 \sin(2\pi ft) \), where \( a_0 = 0.2 \text{ m/s}^2 \) is the minimal amplitude of acceleration for household devices, \( f \) is the frequency of external vibrations, and \( t \) is time. The harvester operates in air under normal conditions. An ideal resistor is connected to the electrodes. The resonant frequency, tip deflection and voltage amplitude, as well as the generated power are investigated.

Modeling of the harvester is performed by a finite element method (FEM). The device is divided into small parts called finite elements, as demonstrated in figure 2. Formulation of boundary conditions results in algebraic equations for each element. These equations include laws of elasticity, electrostatics and piezoelectricity. The Navier-Stokes equation is used to find the quality factor. Solution for large system can be found by assembling approximation function for small elements. The base of the cantilever is fixed, while the whole device is located in the acceleration field. One of the electrodes is grounded. The elements have a shape of rectangular tetrahedron. Their amount depends on the harvester size and varies from \( 7.0 \times 10^4 \) to \( 3.2 \times 10^5 \).

3. Results and discussion
Cantilever without inertial mass in static regime was investigated. The wider the beam, the more charge is accumulated at the electrodes and the higher output current can be generated. This makes wider cantilevers preferable. The tip deflection increases with the beam length and takes the values from 10 to 130 nm. Static output voltage is of 0.04-0.15 mV, depending on \( l \), which is too low to pass the rectifying
circuit that typically requires 0.2-0.3 V [10]. Low voltage is explained by a small stress in AlN. Eigenfrequency $f_0$ of the cantilever without IM is in the kilohertz range, while the external vibrations typically have a frequency below 200 Hz. An addition of the IM with a length $l_m$ of 100-500 μm and width $w_m$ of 1000-1500 μm lowers the frequency to the desired range. The cantilever of 1000x1000 μm in size demonstrates $f_0$ of 45-160 Hz, as shown in figure 3. Thus, the operating frequency can be adjusted by changing the IM size. At the same time, the inertial mass increases the tip deflection, mechanical stress and output voltage, see figure 4. These values are three orders of magnitude higher than those for the beam without IM.

The distribution of stress in the cantilever is presented in figure 5. The largest stress is located at the fixed end. Among the materials used in the harvester, AlN has the lowest tensile strength of 300 MPa [11]. A dependence of maximal stress value on $w_m$ (figure 6) demonstrates that the stress is an order of magnitude lower than the tensile strength. Therefore, the damage of the cantilever during operation is not expected. Extrapolation of the dependence to 300 MPa provides maximal output voltage of 0.9 V.

![Figure 3. Cantilever eigenfrequency dependance on width of IM for different IM length.](image1)

![Figure 4. Cantilever deflection and output voltage dependance on width of IM.](image2)

![Figure 5. Stress distribution in the cantilever with $l_m = 500$ μm and $w_m = 1500$ μm (IM is not shown).](image3)

![Figure 6. The maximal stress value as a function of $w_m$ at $l_m = 500$ μm.](image4)

The vibrating regime is considered for the cantilever of 1000x1000 μm in size, which is equipped by IM with the size of 500x1000 μm. A load resistance is assumed to be $R = 10^{12}$ Ω. According to FEM simulation, the device has a quality factor $Q = 398$ and a resonant frequency $f_r = 55.05$ Hz. The
amplitude of the tip deflection and output voltage as a function of external vibration frequency are shown in figure 7. The bandwidth $\Delta f$ of the harvester is calculated as a width of the resonant peak at a half of its height and equals to 0.14 Hz. In resonance, the device provides the output voltage of 689 mV. The maximal stress in AlN reaches 100 MPa, which is still lower than the tensile strength.

The output power depends on the load resistance, as demonstrated in figure 8. The power and voltage are calculated for $R$ in range from $10^4$ to $10^{10}$ Ω. The current flowing through the resistor has a sinusoidal shape. Therefore, the power is determined as $P = I_R U_R/2$, where $I_R$ and $U_R$ are the amplitude values of the current and voltage at the resistor. The power has a peak of 2.7 nW at the optimal resistance of 25 MΩ. For this resistance, the voltage is 350 mV, which is high enough for rectifying and energy storage. The output characteristics may be improved by optimizing the harvester design. The base layer can be fabricated from the more flexible material [12] or piezo material [13].

Performance of the harvester is convenient to estimate by a figure of merit $F$:

$$F = \frac{P}{(V_b + V_m) \cdot a^2 f_r} \cdot \Delta f,$$

where $V_b = 1.6 \cdot 10^{-6}$ cm$^3$ and $V_m = 2.5 \cdot 10^{-4}$ cm$^3$ are volumes of cantilever and IM, respectively, $a$ is the acceleration amplitude measured in the units of gravity $g$. Piezoelectric harvesters based on AlN typically provide $F$ from 1.5 to 6 $\mu$W/(g$^2$·cm$^3$) [14-16], while the proposed device demonstrates 66 $\mu$W/(g$^2$·cm$^3$). The enhancement is achieved due to a small size and high quality factor. Thus, the compact device outperforms conventional energy harvesters.

4. Conclusions

A piezoelectric energy harvester based on AlN is presented. A key part of the device is a multilayer cantilever with an inertial mass at the tip. Working characteristics of the harvester are calculated by a finite element method. The cantilevers with large lateral size provide higher performance. The beam itself is unable to generate sufficiently high voltage for rectifying and has a resonant frequency in the kHz range. Addition an inertial mass to the cantilever decreases the frequency to required level and increases mechanical stress in AlN, thereby providing higher output voltage. It is worth noting that the stress does not exceed tensile strength of the material. The resonant frequency can be adjusted by varying the size of inertial mass. The proposed harvester demonstrates several times higher high figure of merit than conventional devices, but the output power is rather low. It can be increased by optimizing the cantilever design.

Figure 7. Deflection of the tip and output voltage as a function of excitation frequency.

Figure 8. Output power and voltage as a function of the load resistance.
Acknowledgments
This work was supported by Program no. 0066-2019-0002 of the Ministry of Science and Higher Education of Russia for Valiev Institute of Physics and Technology of RAS.

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