VIBRATION ENERGY HARVESTING
WITH ALUMINUM NITRIDE-BASED PIEZOELECTRIC DEVICES

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Abstract: This paper describes the measurement results of piezoelectric harvesters with AlN as piezoelectric material. The output power harvested from mechanical vibrations has been measured on micromachined harvesters with different geometries. The resonance frequencies ranged from 200 up to 1200 Hz. A maximum output power of 60 µW has been measured at an acceleration of 2.0 g at a resonance frequency of 571 Hz; the power output is of the same level as obtained with devices based on PZT. The package of the harvester requires special attention, since air-damping can significantly decrease the maximum power output.

Key words: energy harvester, piezoelectric, vibration, AlN

1. INTRODUCTION

The power required for a Wireless Autonomous Sensor Node system lies in the range of 100 µW and in order to obtain full autonomy the energy harvester is a key component [1]. Piezoelectric energy harvesters with different dimensions (all below 1 cm^2) have been investigated to cover a broad frequency range (200 up to 1200 Hz) and to find the optimum design for maximum power output. AlN was chosen as piezoelectric material for its material properties. Although the piezoelectric coefficients are lower compared to PZT [2], the electromechanical coupling factor of AlN is comparable due to the lower dielectric constant. As a result, the harvested power obtained with AlN equals or even exceeds the power for PZT based devices. Another welcome advantage is the well-known standard sputter-deposition techniques for AlN in contrast to the more complex deposition of PZT.

This paper will present the experimental measurement method and results. The results will be discussed and finally conclusion will be drawn.

2. EXPERIMENTAL

2.1 Harvester design

Our piezoelectric harvesters consist of a silicon beam and mass and are produced by standard micromachining techniques. The piezoelectric capacitor on top of the beam is formed by a platinum bottom electrode, the AlN layer and an aluminum top electrode. We have produced devices with different beam and mass geometries. An overview of the used dimensions is given in Table 1 in paragraph 2.3. All results presented in this paper are measured on devices with a beam thickness of 45 ± 3 µm and an AlN

thickness of 800 nm. The harvesters are packaged in between two glass substrates with 400 µm deep cavities to allow mass displacement up to the cavity depth. Figure 1 shows the harvester design and its package made of two glass substrates.
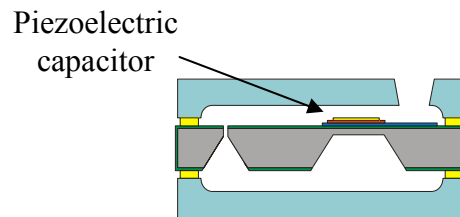

Fig. 1: Vibration energy harvester packaged in between glass substrates.

Both the top and bottom electrode of the piezoelectric capacitor are connected through a contact opening in the upper glass sheet. Electrical contacts are made with wire bonds to a supporting PCB board, see figure 2.
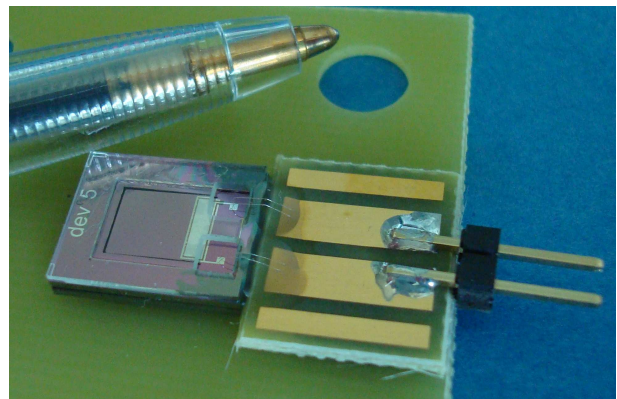

Fig. 2: Vibration energy harvester mounted on a PCB board.

2.2 Measurement method

We have investigated the AlN piezoelectric harvesters with an electrodynamic shaker, by applying a sinusoidal oscillation at varying frequency and constant acceleration as mechanical input. The piezoelectric harvester, represented as a capacitor, will generate an alternating current through a discrete resistive load which is measured with a current meter, see figure 3.
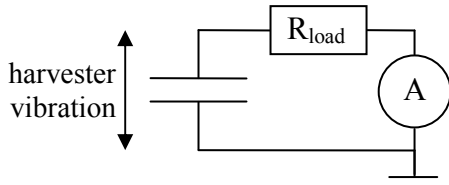

Fig. 3: Electrical measurement scheme.

For an optimum power output the load resistance was matched to the impedance of the harvester. Figure 4 shows an example of the output power as a function of the load resistance. For the AlN devices the optimum load resistance was found in the range of 0.1-1.0 MΩ. Compared with PZT devices, which usually have an optimum load resistance of a few kΩ, the AlN devices require a higher load resistance. The voltage level over the resistive load is in the range of a few volts. PZT based devices have a much lower voltage level. The higher voltage level of AlN based devices is favorable for future power processing circuits, like rectifiers or battery chargers. This might make voltage–upconversion redundant.
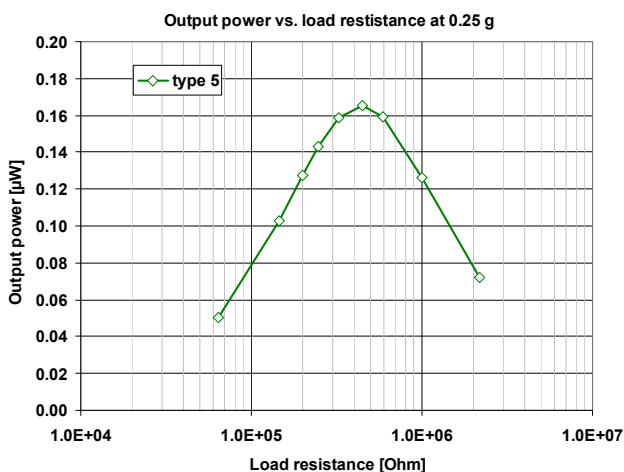

Fig. 4: Load resistor matching for device type 5 at 0.25 g at resonance.

The power dissipated in the resistive load is calculated according to (1) using the measured RMS value of the AC-current and the used discrete load resistor value.

$$P = I_{RMS}{}^2 \cdot R \qquad (1)$$

2.3 Measurement results

In Figure 5 the resonance curves of devices with different dimensions, as given in table 1, are presented at an acceleration level of 2.0 g. It shows that by controlling the dimensions of the beam and mass the resonance frequency can be set.
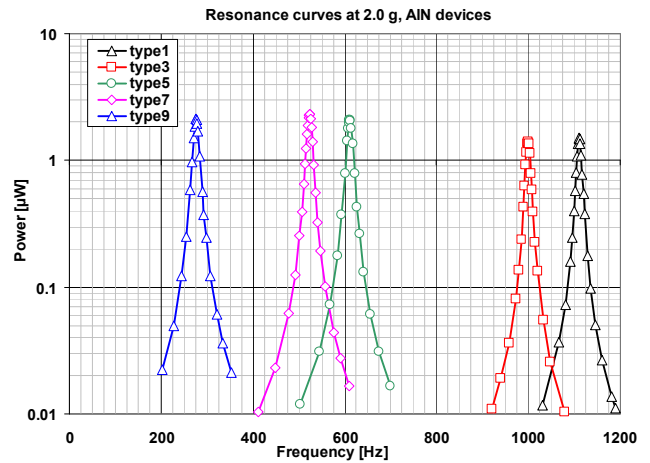

Fig. 5: Resonance curves for devices with different geometry. They are packaged, which causes considerable air-damping and decreases the output power.

Table 1: Beam dimensions in mm, frequencies in Hz.

Device type	Beam length	Mass length	Beam width	Resonance frequency
1	1.31	3.0	3.0	1110
3	1.61	3.0	3.0	1000
5	1.01	5.0	5.0	611
7	1.29	5.0	5.0	523
9	2.10	7.0	7.0	277

Both analytical and numerical models of the harvester design have a good overlap with the experimental data [3]. The output powers for these packaged devices are all in the range of 1 to 3 µW.

One should consider that the amount of air-damping is dependent of the beam and mass size. A device with a larger surface area will have a higher air-damping coefficient.

Figure 6 shows resonance curves at acceleration levels from 1.0 g up to 8.0 g. These measurements were performed on a device which has a package as shown in figure 1 with considerable air-damping. This air-damping results in a significantly reduced maximum power output and low quality factors. In this case a power output of 17 µW is measured at an acceleration of 8.0 g.

The maximum mass tip displacement is limited by dimensions of the cavity and is at maximum 400 µm from the initial position. For this device the

displacement at 8.0 g was about 250 µm. Further below we will show results measured with an unpackaged device with less damping and therefore higher mass displacement leading to higher output power at lower acceleration.
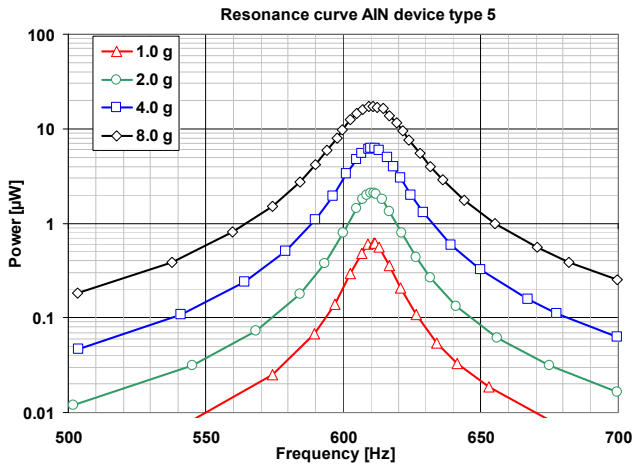

Fig. 6: Resonance curves at different acceleration forces.

The quality factor decreases at higher accelerations. For these measurements the quality factor dropped from 42 to 25 for acceleration levels of 1.0 g and 8.0 g respectively. This decrease of the quality factor can be seen in the figure as a broadening of the resonance curves. The cause of this decrease is the air-damping, which is a mechanical loss factor.

Figure 7 shows the resonance curve of a device type 5 without a package, the beam can move unlimited in open air. The resonance curve is slightly asymmetrical, most likely due to non-linear behavior at these large mass displacements.
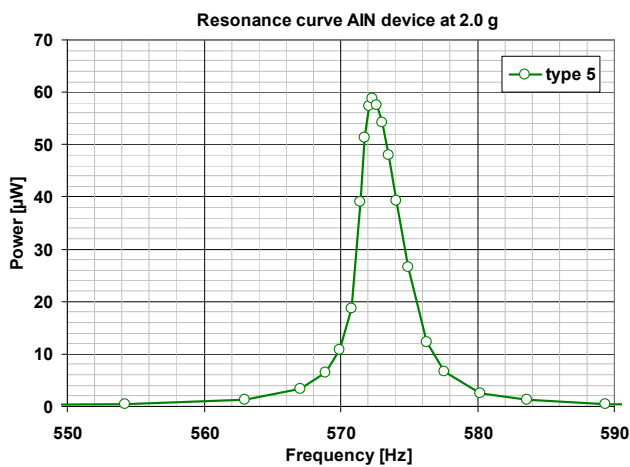

Fig. 7: Resonance curve of a device type 5, maximum output power of 60 µW at 2.0 g, without a package.

The output power at resonance is 60 µW, and is comparable with devices using PZT as piezoelectric material [2]. The input acceleration was 2.0 g, this equals a peak to peak input displacement of 3.03 µm at the resonance frequency of 572 Hz. The maximum peak to peak displacement at the tip of mass was 895 µm, which was measured with an optical microscope. The quality factor as obtained from a mathematical fit to the resonance curve is 170. The mechanical amplification factor is calculated by dividing the displacement at the center of the mass by the input displacement and should equal the quality factor. For this device the mechanical amplification factor equals 160. The difference between the quality factor and the mechanical amplification factor is considered to be within the measurement accuracy.

For this device without package the output power as a function of the input acceleration at the resonance frequency is shown in figure 8. At low acceleration levels up to about 1.0 g the slope of this double logarithmic plot is close to +2, indicating a quadratic relation between output power and input acceleration. At higher acceleration levels the slope reduces towards a value of +1, which indicates a linear relation. This change from quadratic to linear behavior can be a result of the relatively large mass displacement and thus a large beam bending which is about 2 degrees. Another possible cause is that the air-damping increases at higher mass velocity occurring at larger mass displacement.
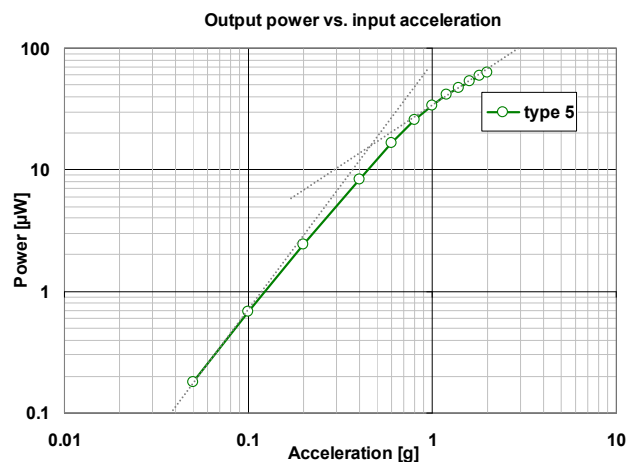

Fig. 8: Power output as a function of input acceleration at the resonance frequency.

A comparison between three devices type 5 with different air damping is visualized in figure 9. The packaged device generates an output power of 2.1 µW. The device on which the package is partly opened at the mass tip generated 22 µW. The device without a package generated 60 µW; all measurements were

performed at 2.0 g. The corresponding quality factors are 37, 110 and 170 respectively.

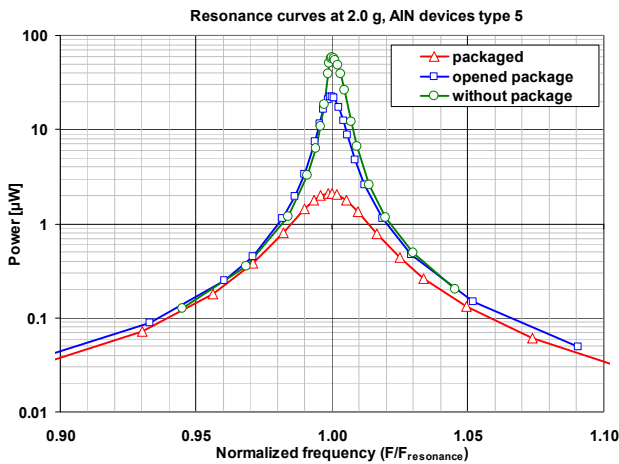**Resonance curves at 2.0 g, AlN devices type 5**

Fig. 9: Resonance curves of three similar devices with different air-damping.

The frequency scale on the x-axis is normalized to compensate for a small frequency shift between the three devices caused by a small difference in beam thickness due to process variation over the wafer. The air-damping reduces the displacement of the vibrating beam and thus introduces mechanical loss, which is best expressed in the reduced quality factor. As one can see, the bandwidth increases when air-damping is present. However, there is no gain in power output at any frequency. The result of air-damping is suppression of the resonance peak, which leads to a lower output power.

A further improvement can be expected when air-damping is prevented with vacuum packaged devices. In that case the moving mass is not damped and will have a larger displacement at lower excitation force, leading to a higher power output and higher quality factor.

3. CONCLUSION

We presented in this paper measurement results of AlN piezoelectric energy harvesters. The output power harvested from mechanical vibrations has been measured on micromachined harvesters with different geometry. The resonance frequencies ranged from 200 up to 1200 Hz. A maximum output power of 60 µW has been measured at an acceleration of 2.0 g at a resonance frequency of 571 Hz, which is comparable to devices with PZT. AlN was chosen as piezoelectric material for its material properties and for its easier processing. The devices were packaged with a top and bottom glass substrate with cavities to allow mass

displacement up to 400 µm. The air-damping caused by the package broadens the bandwidth, but there is no gain in power output at any frequency. Air-damping is only a loss factor and should be minimized for a maximum power output. It is expected that higher output power and quality factor can be obtained with a vacuum package design.

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