# ALN BASED PIEZOMICROGENERATOR FOR IMPLANTS

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**Abstract:** In this work we report on energy harvesting microstructures based on AlN. Experimental results on the mechanical and piezoelectrical properties of sputtered AlN thin films deposited on Si(001) substrates as well as results on vibrometry and piezo-generation of fabricated microstructures are presented. It is shown that due to the constant $d_{33}$ piezo coefficients of > 5 pm/V and advantageous mechanical properties, AlN films are well suited for the integration in cantilever or membrane structures for powering of low-consumption sensor networks.

**Keywords:** aluminum nitride, MEMS, piezogenerator, nanodiamond

## INTRODUCTION

Piezoelectric thin films have recently attracted much attention due to their applicability in vibration energy harvesting micro systems, e.g. for implantable sensor networks [1]. In particular, thin film based piezo microstuctures are showing a very good coupling efficiency of the transducer and exhibit a relatively simple configuration. It can potentially provide enough power to operate a 10 mW device at reasonable intermittent rates [2]. Due to their microfabrication advantages, chemical inertness and biocompatibility [3], AlN unimorph piezo-devices offer an essential advantage over Pb- and Zn-containing solutions, being well suited for the integration in implants as sensors as well as power supplies to monitor human body parameters, e.g. the intraocular or arterial pressure. Further advantages for the integration are compatibility with CMOS drivers. The recent works show promising properties of sputtered AlN thin films for energy harvesting. However, the reported structures are still not well suited for implants due to either their large dimensions or complex technology issues [4,5].

In this work we report on mechanical and piezoelectrical properties of AlN thin films along with microfabrication of membranes and cantilevers and their tests towards the piezogeneration at ambient conditions.

## EXPERIMENTAL

AlN films were deposited by RF magnetron sputtering using 6N Ar/N2 mixture at room temperature on Si(001) substrates. AlN textured deposit possesses tunable low strain [6], which can be orders of magnitude lower as those existing in single crystalline epitaxial structures [7].

In our studies, the films attached to the wafers as well as tensile strained thin membranes were investigated. The studies of crystal quality and morphology of the films was carried out by X-ray diffractometry (XRD) and atomic force microscopy (AFM), respectively. The crystal quality of deposited layers has been then compared quantitatively and qualitatively using an FWHM value of the rocking curves around the 00.2 AlN Bragg reflection and analysis of Θ/2Θ-curves taken at the identical conditions, respectively. As a brief summary, the various XRD patterns of AlN films (not shown here) grown on rough surfaces reveal a high degree of random tilts of the crystallites composing the sputtered film independent of the template material used. It is due to the fact that each AlN domain in the texture tends to grow with its (00.1) planes parallel to the template surface rather than parallel to the appropriate crystallographic planes of the underlying substrate grains [8]. The typical FWHM values of the rocking curves measured on 120 nm thick AlN films deposited on Si (AFM rms<0.2 nm) and polished nano crystalline diamond (rms~2 nm) are 3.22° and 5.20°, respectively. The root mean square (rms) surface roughness have been calculated from 2x2 $\mu m^2$ AFM topographies.

The pole figures taken at the 2H AlN 10.1 reflection position also indicate a preferential c-orientation of the layer's columnar structure deposited on a flat template. In contrast, the pole figures of AlN deposited on rough layers shows homogeneous distribution of the XRD intensity indicating much more random orientation of the AlN grains with a significant deviation from the c-orientation [9].

The unimorph and single layer membranes with diameters of 0.8 – 3 mm have been fabricated from thin films and heterostructures deposited on silicon using a backside deep reactive ion etching (DRIE). The membranes were metalized from both sides to allow the piezoelectrical actuation of the system. The resonant frequencies of thin membranes have been measured using internal piezoelectrical and external mechanical excitation of the membranes.

For cantilever fabrication, after sputtering of a 200 nm AlN layer on to Si(001) substrate, the top electrode was formed by evaporating of Al (50 nm) and structuring it by a lift-off process. For the deep etching of Si/AlN/Al-structure an inductive coupled plasma (ICP) $BCl_3/Cl_2$ process was used. The silicon underetching for cantilever release was carried out via

SF6- plasma etch process. A back electrode was fabricated by evaporating of Al (200 nm) prior to the deposition of AlN layer. The length and width of fabricated cantilevers ranged from 25 to 250 µm and from 2 to 12 µm, respectively.

The out-of-plane displacement of the surfaces were measured by a laser Doppler vibrometry (LDV) method [10] with a precision below 1 pm. For this purpose a Polytec MSA-500 vibrometer has been used, which was equipped with the amplitude (30 KHz – 20 MHz) detector. For the generation of an external electrical signal an Agilent 33250A function generator has been employed. For the external mechanical excitation, a PZT stack actuator was used.

## RESULTS AND DISCUSSION

LDV of 200 nm thick AlN films reveals the stable, frequency independent piezo-response ($d_{33}$ ~ 5-6 pm/V) showing a good applicability of the material for the autonomous microgenerators.

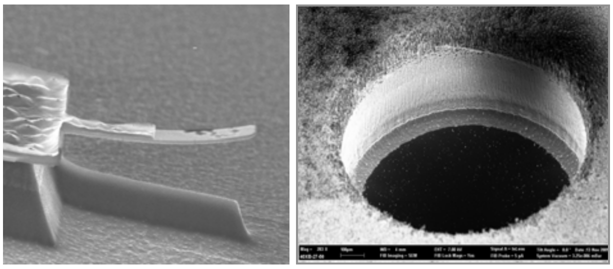

*Fig. 1: Examples of piezogenerating AlN microstructures: a) cantilever and b) circular membrane.*

Using LDV, a quality factor $Q$ of ~ 50-80 was measured for microcantilevers shown in Fig. 1a at ambient conditions. The Young's modulus of ~310 GPa and the acoustic wave velocity of $\sqrt{E/\rho}$ ~ $10^4$ m/s have been derived for the AlN thin films being in agreement to literature values. In addition, for a 75 µm long and 4 µm wide Al/AlN/Al microcantilever, the generated voltage of ~ 200 µV was registered at the resonant frequency of 72.5 kHz with a tip deflection of ~70 nm.

Afterwards, the piezoelectric AlN membranes (Fig. 1b) have been tested towards energy conversion efficiency in different environments. Firstly, the eigenmodes and eigenfrequencies of contact free membranes have been analyzed using piezoelectrical and external mechanical excitation methods at a wide frequency range, in order to determine the material properties (Fig. 2). LDV method has been applied to study the resonant mode shapes and frequencies of thin circular AlN membranes in order to evaluate the mechanical properties of the material. The quality factor $Q$ ~ 40000 was obtained for the best resonators *in vacuo* indicating negligible deviations of the material and geometrical properties over the membrane.

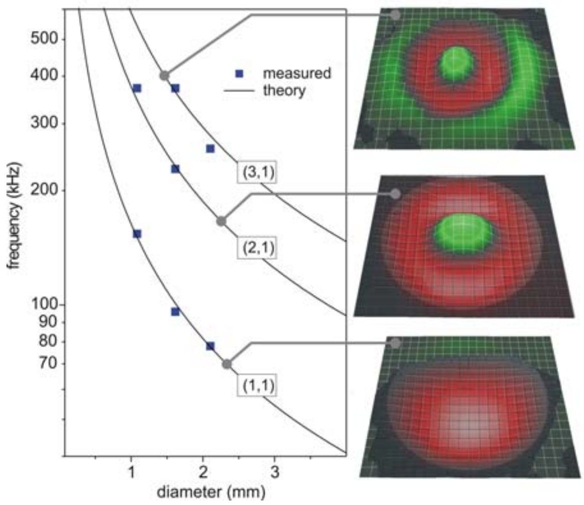


*Fig. 2: Resonant frequencies of the first three vibration eigenmodes recorded by LDV on AlN membranes excited mechanically.*

The experimental resonant frequencies (represented in Fig. 2 by the squares) have been parametrically fitted using an equation for resonant frequencies of circular membrane of radius $R$:

$$\omega_{ji} = \left( \sqrt{\frac{T}{d\rho}} \beta_{ji} \right) / R$$

where the matrix $\beta_{ji}$ represents the $j^{th}$ zero of the $i^{th}$ Bessel function, $J_i$, $d$ is the thickness, $\rho$ is the density of material, and $T$ is the tension. T was used as a fit parameter. The averaged value of $T$ ~ +50.4±0.8 N/m (the stress $\sigma$ = $T/d$ ~ 230 MPa) has been derived for the measured sample series. Thus, no impact of membrane size on the residual stress value was observed indicating a high reliability of the deposition and DRIE technologies.

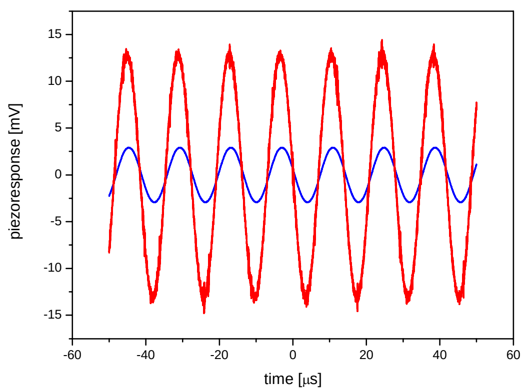


*Fig. 3: Piezoresponse of the membrane device (the red curve) on the mechanical excitation at the frequency of 71 kHz at ambient conditions.*

The membranes with circular top contacts were then mechanically excited using a PZT stack at intrinsic fundamental resonance frequency $f_{1,1}$ at ambient conditions. The piezoresponse (the red curve) registered by the oscilloscope with input impedance of 1 MOhm is shown in Fig. 3 together with excitation signal (shown in blue) applied to the piezo stack.

Afterwards, the piezoelectric AlN membrane have been measured using a pulse mode excitation simulating blood pressure variations within the human body. The mechanical distortions of the membrane have been performed by PZT stack and signal generator. The signal frequency and duration of the pulse were 20 Hz and 18 μs, respectively. As shown in Fig. 4, the pulse first charged the internal capacitance of the membrane $C \sim 1$ nF. The discharge of the capacitance within the decay time $\tau \sim RC \sim 0.04$ ms is superimposed with a pizoelectrical signal generated by the damped vibration of the membrane in air. From these measurements, the quality factor and the damped resonant frequency of the membrane were deduced to be about $Q \sim 25$ and $f_{1,1} \sim 28$ kHz, respectively.

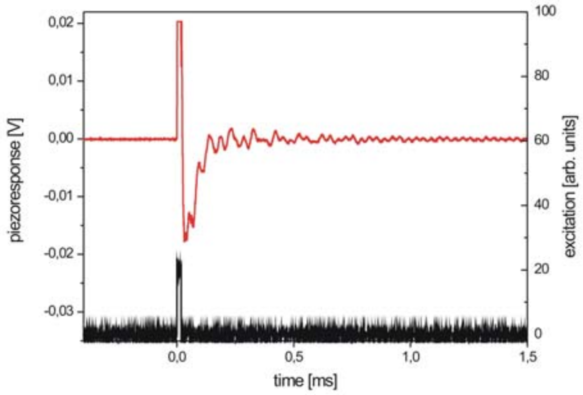


*Fig. 4: Piezoresponse of the membrane device (the red curve) on the mechanical pulse with duration of 18 μs and frequency of 20 Hz at ambient conditions.*

Finally, the impact of the complex acoustic signal on the piezoresponse of the membrane has been measured using sound waves with a duration of about 4 ms and frequency of 1 Hz generated by a conventional loudspeaker. The peak sound pressure in this experiment was about 0.632 Pa (~90 dB). The registered piezoresponse is shown in Fig. 5a. In Fig. 5b, the fast Fourier Transform (FFT) of the signal is shown. The plot represents two resonant frequencies of the membrane. The peaks marked by (1) and (2) belong to the low frequency (1,0) and (1,1) mode of the system comprising the membrane and top circular contacts. The high frequency peak at 71 kHz marked by (3) is the resonant frequency of the contact free part of the membrane.

## CONCLUSION

The measured frequency independent piezo-response of AlN-based structures ($d_{33} \sim$ 5-6 pm/V) shows a good applicability of the material for the autonomous energy harvesting devices.

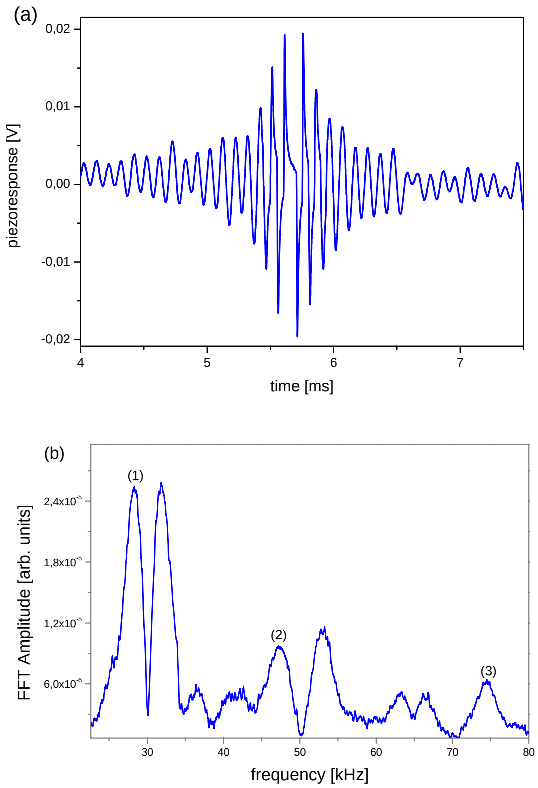


*Fig. 5: Piezoresponse of the membrane device on the acoustic signal at ambient conditions (a) in time domain, and (b) in frequency domain.*

It was shown that Al/AlN/Al microcantilevers allow to generate ~ 200 μV at the resonant frequency of 72.5 kHz with a tip deflection of ~70 nm. The piezo membranes generate typical voltages up to 40 mV at the resonant frequencies and during excitation by either moderate mechanical or acoustic pulses.

Since usual requirement for piezoelectric energy converters is a power generation of ~1 μW at 0.5 g to supply low-consumption sensor units, the fabricated microstructures should be used in a parallel or serial assembly to supply low consumption sensor nodes (~1 μW), charging an accumulating capacity within a few minutes.

## ACKNOWLEDGEMENT

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## REFERENCES

[1] S. P. Beeby, M. J. Tudor, and N. M. White, Meas. Sci. Technol. 17 (2006), p. 190.

[2] W. W. Clark and Ch. Mo in Energy Harvesting Technologies, Springer, 2009, pp. 405-430.

[3] I. Cimalla et al., Sensors and Actuators B, 123, 740 (2007).

[4] R. Elfrink, T. Kamel, M. Goedbloed, S. Matova, D. Hohlfeld, Y. van Andel, and R. van Schaijk, J.

Micromech. Microeng. 19 (2009).
[5] M. Marzencki, M. Defosseux, and S. Basrour, J. Microelec-tromech. Syst. 18, 6, 1444 (2009).
[6] R. E. Sah, L. Kirste, M. Baeumler, P. Hiesinger, V. Cimalla, V. Lebedev, H. Baumann, and H.-E. Zschau, J. Vac. Sci. Tech. A 28, 394 (2010); R. E. Sah, L. Kirste, M. Baeumler, P. Hiesinger, V. Cimalla, V. Lebedev, F. Knöbber, O. Bludau, C. C. Röhlig, and H. Baumann, Proceedings of the 2010 NSTI Nanotechnology Conference 2, 347 (2010).
[7] V. Lebedev, V. Cimalla, U. Kaiser, Ch. Foerster, J. Pezoldt and O. Ambacher, J. Appl. Phys. 97, 114306 (2005).
[8] V. Lebedev, J. Jinschek, U. Kaiser, B. Schröter, W. Richter, J. Kräußlich, Appl. Phys. Lett. 76, 2029 (2000); V. Lebedev, J. Jinschek, J. Kräußlich, U. Kaiser, B. Schröter, W. Richter, J. Crystal Growth 230, 430 (2001).
[9] F. Knöbber, O. Bludau, C.-C. Röhlig, O. Williams, R. E. Sah, L. Kirste, V. Cimalla, V. Lebedev, Ch. Nebel and O. Ambacher, ISCS 2010, Kagawa, Japan (2010).
[10] R. Herdier, D.Jenkins, E. Dogheche and D. Rèmiensb, M.v Sulc, Rev. Scie. Instr 77, 093905 (2006).