Abstract—Investigations were carried out on the usability of aluminum nitride thin films for the manufacturing of ultrasound transducers by the use of sensor test structures. Some design considerations were performed for different sensor designs, electrode size variations and substrate materials in this work. It could be shown that the electrode size can be smaller than 1 mm square for use as high frequency sensors. Different substrate materials are principle usable, like e.g. silicon, aluminum oxide or quartz. Additional tests showed that these sensors can also be used for high temperature application up to 200 °C. The reason is the very good temperature resistance of the AlN thin films.

Keywords: ultrasonic high frequency sensor; Aluminium nitride thin film;

1. Introduction

New 3-dimensional integrated electronic devices, next generations of textured materials like carbon fiber reinforces polymers (CFRP) and complex multilayered devices like solar cells require new approaches for non destructive evaluation techniques. Ultrasonic microscopes are frequently used for the non-destructive evaluation of micro-technical components and structures; because of their versatility and efficiency. The frequency of an ultrasonic test system defines the attainable resolution and the penetration depth into a material. The efficiency of conventional microscopes can be enhanced by a combination with high frequency phased array (PA) techniques. With the use of segmented transducers (~ into pixels divided sensors), it is possible to evaluate the whole volumes of specimen in 3 dimensions. The advantage is that the ultrasonic transducer does not need to be manipulated mechanically by a scanner. The shape and the sound beam direction can be controlled on a large scale since each of the array elements can be pulsed with appropriate time delays. At present PA ultrasonic sensors with working frequencies up to 20 MHz are available, but frequencies above 50 MHz are necessary for the applications that require a high resolution. Therefore new high frequency PA sensors need to be developed.

The very high frequencies in phased array sensors require a very thin transducer thickness and cannot be realized with traditional piezoelectric materials like PZT ceramics, piezoelectric 1-3 composites or polymers like polyvinylidenfluoride (PVDF). A promising alternative piezoelectric material is aluminum nitride (AlN). Aluminum nitride is a piezoelectric but not ferroelectric material with a Wurtzite crystal structure. Compared to the widely used ferroelectric materials like PZT, AlN need not be electrically polied. Therefore piezoelectric activity can only be achieved with single crystals or with a polycrystalline structure with a strong crystal orientation (Fig. 1). To achieve a thickness vibration of the sensor, a crystalline orientation in (001) direction is necessary (c-axis of the AlN crystalline structure being oriented perpendicular to the substrate surface). AlN in this condition exhibits several attractive properties that were verified in various publications (e.g. 1) and in our own experimental work:

− Piezoelectric coupling coefficient of 20 %
− Piezoelectric constant d_{33} of about 8 pm/V
− Piezoelectric constant g_{33} of about 100 mVm/N
− High sound velocity for longitudinal waves 10700 m/s
− High dielectric strength of up to 20 MV/cm
− Low dielectric constant of 8,6
− High electrical resistivity of more than 10^{11} \Omega cm
− High temperature stability (up to 1000°C)
Additionally the AlN thin film technology is compatible to CMOS technology and semiconductor processes therefore interesting in MEMS (Microelectromechnical Systems) and MOEMS (Microoptomechanical Systems) fabrication. Recent publications show, that for these applications very thin films (below 1µm, e.g. 2) were deposited with deposition rates between 5 nm/min 3 and 100 nm/min 4. But until now AlN is seldom used for ultrasonic transducers, only a few groups are working on single element ultrasonic transducers for low frequencies based on membrane vibration 5 or based on thickness vibration to reach a high resonance frequency of 100 MHz 6. Further investigation on the behaviour of thin film AlN piezoelectric sensors and design consideration need to be performed.

![SEM-micrographs of AlN films, thickness 10µm](image)

**Figure 1.** SEM-micrographs of AlN films, thickness 10µm

### 2. Test Setup and Measurement Methods

A simple layout was used for optimization of deposition process in previous investigations [7, 8]. Here additionally sensor investigations were carried out for high temperature storage; and design considerations performed for different substrate materials with the same test layout. An electrode structure with 10 mm diameter was deposited on an isolated substrate. An aluminium nitride film in a circle structure with a diameter of 13 mm was deposited, followed by a second aluminium electrode to fabricate the sensor and the interconnection pad on the top side as shown in Fig. 2. The aluminum electrodes all have a thickness of 150 nm.

![Ultrasonic sensors on different materials (silicon, kapton, aluminium, quartz, Al2O3, glass)](image)

**Figure 2.** Ultrasonic sensors on different materials (silicon, kapton, aluminium, quartz, Al2O3, glass)

Additionally design considerations were carried out with different electrode sizes. The layer thicknesses and sequence are same as we used in the first experiments [8]. Only the layout was changed as can be seen in Fig. 3. The bottom electrode is a square shaped aluminum electrode with a large ground area around for a better electromagnetic shielding. On top of the bottom electrode a square shaped AlN Layer with a thickness of 10 µm and an edge length of 5 mm follows. The top electrode is also square shaped with the same edge length as the bottom electrode and a short track for the connection of the measurement tips. Sensors with edge lengths of 5 mm, 1 mm, 0.5 mm and 0.3 mm were manufactured with the optimized sputtering parameter sets on a 6” silicon wafer. The bottom electrode for the smallest electrode size of 0.3 mm was 0.5 mm to reduce effects caused by a misalignment of the masks. The optimized unipolar and bipolar deposition parameters were used for the deposition of 6” isolated silicon wafers with 17 pieces of the same geometry on each substrate.
2.1 Pulse Echo Measurements

The sensor tests were performed with the pulse echo measurements too [7]. The AlN sensor served as an acoustic transmitter and receiver. The pulser and receiver DPR 500 (JSR Ultrasonics) was used to excite an acoustic sound wave. The ultrasound wave propagates through the substrate, is reflected at the interface substrate-air and travels back to the AlN layer. There the ultrasound wave excites a voltage signal which can be measured and evaluated (Fig. 4).

The maximum amplitude of the received voltage signal was used to evaluate the AlN film quality depending on the deposition parameters. The measured voltage values were calculated to absolute voltage values without gain for a better comparability. The Fig. 5 shows a typical time response with multiple back wall echoes. To avoid an influence of the sending signal, we did not evaluate the first back wall echo but the fourth.
2.2 Measurements of piezoelectric constant $d_{33}$

The piezoelectric charge constant $d_{33}$ was determined with a conventional Berlincourt-Meter (Piezotest PM300). The samples were clamped and loaded with an alternating force. The generated electric charge was compared to the value of a reference sample to obtain the piezoelectric charge constant. The measurements were carried out by applying an alternating force of 0.25 N and a frequency of 110 Hz; see [7]. Additional test specimens with new substrate materials were created after the optimization of the AlN thin film deposition process. Different substrate materials, like aluminium oxide, glass, quartz and aluminium were investigated. This is important for the sensor design considerations, because different substrate materials have different mechanical and acoustic properties, which have an influence on the thin film ultrasonic transducers. The mechanical clamping of the thin film to the substrate plays an important role as well as the geometry dimensions. The relative big thin film sensor area in versus to the thin film thickness has a second influence on the $d_{33}$ measurement with this method. This takes effect as a second clamping.

![Figure 6. Schematic of $d_{33}$-Meter](image)

3. Experiments and Results

3.1 Substrate variation and temperature storage

In Figure 7, the fourth back wall echoes are shown for the optimized layers deposited in the unipolar and bipolar pulse mode as well as for a not optimized layer. Strong differences in the transmitting and receiving properties of AlN based sensor could be verified as result from the different sputtering and deposition parameters.

![Figure 7. Examples of signal amplitudes of one back wall echo depending on the deposition parameter set](image)

An acceptable piezoelectric activity could be proofed on a variety of substrate materials, which are common in electronics manufacturing, using sputtering parameter sets found in earlier investigations [7]. The $d_{33}$-meter can be used for a very fast estimation of the thin film quality for AlN sensors with the same substrate material and film thickness (see Fig. 6).
The measured value $d_{33}$ is not the actually $d_{33}$ value of the AlN thin film. This follows from the mentioned clamping of the thin film transducer on the substrate. During the testing with the $d_{33}$-meter the sample should only be loaded by the force head with a stress in thickness direction, which means parallel to the crystal orientation to obtain an unaffected $d_{33}$ value.

In this case an additional stress in planar direction is induced, because of the clamping of the thin film on the substrate and because of the very low ratio of film thickness to diameter. Therefore the measured $d_{33}$ value is lower than the true value and depends on the Poisson ratio of the substrate material. The lower the Poisson ratio of the substrate is, the lower is the measured $d_{33}$ value. The rather hard materials which have a lower Poisson ratio and a lower elongation coefficient (e.g. 2.0 for silicon and 23.0 for aluminium $\alpha$ in $[10^{-6}/K]$), show also lower $d_{33}$ measurement results. This relationship can be seen in Fig.8. We also can correlate the measured $d_{33}$ values of the test sensors with the signal amplitude maximums and have well accordance.

Additionally the sensors with different substrates were stored at high temperatures to evaluate the influence on the piezoelectric properties of the AlN and the substrate. The maximum signal voltages of the pulse echo measurements of all sensors were obtained, but a direct comparison was not possible because of the different substrate thicknesses and acoustical damping coefficients. Monocrystalline silicon has a much lower damping coefficient compared to the other substrate materials and therefore the maximum voltage received is much higher. For all materials it is obvious, that the temperature storage at 200°C had no significant influence.
For aluminium, aluminium oxide and silicon no change in the $d_{33}$ value could be observed, but the $d_{33}$ value of glass seemed to be much higher. Due to the fact, that there was no change in the measured back wall echo amplitude, it can be assumed that this effect is not caused by a change of the AlN properties, but by a change of the glass structure.

### 3.2 Electrode Size Variation

The variation showed a detectable reflected ultrasound wave for all electrode sizes, but for different electrode sizes the signal form and amplitude is also different.

The overview of the measured maximum signal amplitudes is shown in Fig. 12. For both parameter sets the electrodes with 1 mm$^2$ showed the highest signal amplitude. All measurements were done with a conventional pulser-receiver with an input impedance of 50 Ω without additional impedance matching of the sensors. The impedance of the sensors with an electrode area of 1 mm$^2$ fits best to the characteristic impedance of the measurement cables used and the input impedance of the hardware. The reflection coefficient for these sensors is much lower than for the sensors with other geometries. The matching of the electric impedances, the sensor size and the film properties influence the maximum signal amplitude. Therefore there is no direct dependency visible between the maximum signal amplitude and the electrode area. But we could prove that it is possible to send and receive ultrasound waves with very small electrodes, which is important for an application of these films in phased array ultrasound transducers.

The variation of the mean values for the unipolar mode is between 7.5 % for the 1 mm$^2$ electrodes and 15.6 % for the 25 mm$^2$ electrodes. The variation of the values for the bipolar mode is higher. It varies between 15.7 % for the 0.25 mm$^2$ electrodes and 21.5 % for the 25 mm$^2$ electrodes. These results are also investigated and are influenced by the electrical matching.

![Figure 11. Back wall echo for square shaped electrodes with edge lengths of 1 mm.](image)

![Figure 12. Maximum amplitude $|V_{\text{max}}|$ of the 4th back wall echo without additional gain for square shaped electrodes with edge lengths of 0.3 mm, 0.5 mm, 1 mm and 5 mm.](image)
4. Conclusion and Vision

Basic investigations were carried out for different ultrasonic thin film AlN sensor designs, electrode sizes and substrate materials. It could be shown that the electrode size can be smaller than 1 mm square for use as high frequency sensors. Additionally test of different substrate materials have shown, that this sensor substrates can also be use in higher temperature application up to 200 °C. The reason is the very good temperature resistance of the AlN thin film transducers. The sensor design was varied for these investigations. Different substrate materials are principle usable, like e.g. silicone, aluminum oxide or quartz.

The development of thin film based ultrasonic sensors should enhance the application range of ultrasonic microscopes. Especially the non-destructive evaluation becomes more and more important for micro-technical components, heterogeneous structures, new materials like reinforced carbon fiber composites and thin film components in the flat screens or solar cells. With the use of phased array sensors working in higher frequency range then today available, this technique will become more effective. The vision of the project idea is the development and demonstration of a new ultrasonic sensor test system with high frequency phased array transducer for the evaluation of complex three-dimensional components, structures or medical Applications. Therefore a new phased array sensor has to be developed on the basis of piezoelectric thin films. A demonstrator working in a frequency range above 50 MHz in phased array technique with multi-channel electronic will be created in further investigations.

ACKNOWLEDGEMENTS

This work has been partially supported by a Grant-in-Aid for Technology Funding by the European Regional Development Fund (ERDF) 2007-2013 and the State of Saxony as well as by Fraunhofer-Gesellschaft. Many thanks also to Fraunhofer Institute for Electron Beam and Plasma Technology FEP in Dresden for the deposition processes and micro analyses by SEM and XRD.

References