Investigations on aluminum nitride thin film properties and design considerations for smart high frequency ultrasound sensors

Susan Walter, Thomas Herzog, Henning Heuer,
Fraunhofer Institute for Non-Destructive Testing,
IZFP Dresden Branch,
Dresden, Germany
Thomas.Herzog@izfp-d.fraunhofer.de

***Abstract*— Basic investigations were carried out on the usability of aluminum nitride thin films for the manufacturing of ultrasound transducers. Some design considerations were performed for different sensor designs, electrode sizes 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. silicone, 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. The sensor design was varied for these investigations and simulations based on a MASON model assisted the material considerations.**

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

I. INTRODUCTION

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 higher the frequency is, the better is the resolution and the smaller is the penetration depth. 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.

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 can not be electrically poled. Therefore piezoelectric activity can only be achieved with single crystals or with a polycrystalline structure with a strong crystal orientation. 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} Ωcm
- High temperature stability (up to 1000°C)

Additionally the AlN thin film technology is compatible to CMOS technology and 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.

II. TEST SETUP AND MEASUREMENT METHODS

A simple layout was used for optimization of deposition process in previous investigations [7]. 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 silicon wafer. 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. 1. The aluminum electrodes all have a thickness of 150 nm. These deposition processes were carried out at Fraunhofer Institute for Electron Beam and Plasma Technology - FEP in Dresden.

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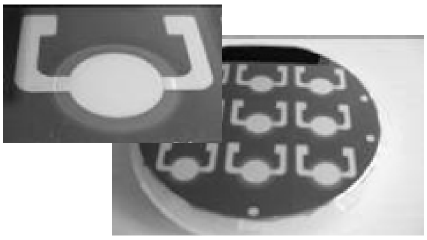

Figure 1. Ultrasonic sensors on silicon wafer

Additionally design considerations were carried out with different electrode sizes. The layer thicknesses and sequence are same as we used in the first experiments. Only the layout was changed as can be seen in fig. 2. 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.

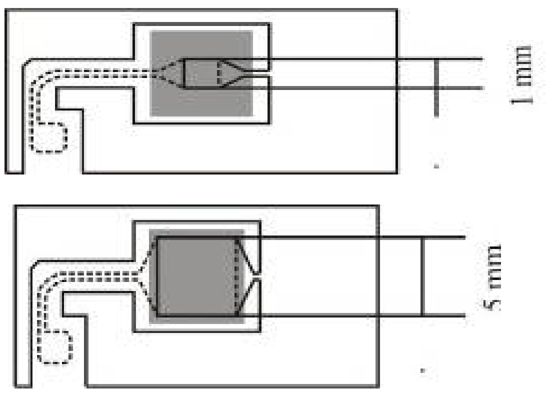

Figure 2. Layout for electrode size variation experiments with coaxial bottom electrode (full line), AlN layer (grey) and top electrode (dashed line), exemplarily for 1 mm² (left) and 25 mm² (right).

A. 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.

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. 3 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.

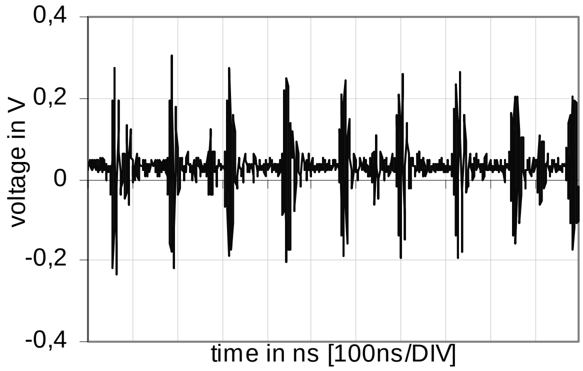

Figure 3. Echo pulse signal from silicon back wall reflection

B. 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 specimen 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.

C. Modelling of sensor design for single element transducer

The basis for the simulation of different thin film sensor designs and substrate materials was a MASON model. This model was created by electrical engineering values for the piezo-effect. The Model in these investigations was build in PSpice and consists of a transmission line driven by an ideal transformer (fig. 4). The single element transducer in this transmission line was described by modelling of all layer materials, and therefore the material properties needed to be known.

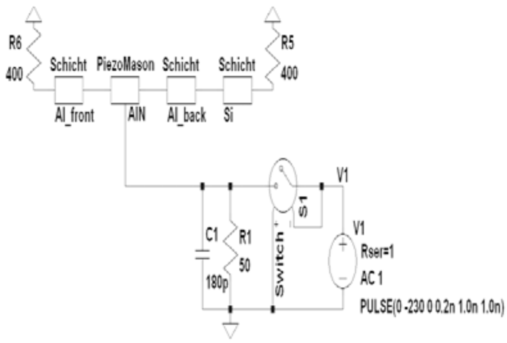

Figure 4. PSpice-Model of a AlN single element transducer

D. *Measurements of warping with Laser vibrometer*

The warping vibration of the sensor thin films of the single transducer was determined with an ultra high frequency Laser vibrometer UHF-120. The investigation took part at Polytec laboratories. This measurement system is able to detect mechanical vibration up to 1.2 GHz. Other conventional Laser vibrometers are only working in the frequency range of 20 MHz and couldn't be used here.

A sinusoidal voltage with an amplitude of +/- 3 V was applied to the single element transducers to realize a continuously excitation and vibration. The mechanical warping of the thin film elements was measured in z-direction in a range of some 10 pm. Afterwards the exciting frequency was raised continuously to detect the resonance frequencies of the thin film sensors. Additionally the laser worked in a scanning mode to evaluate the vibration pattern of the complete sensor surface.

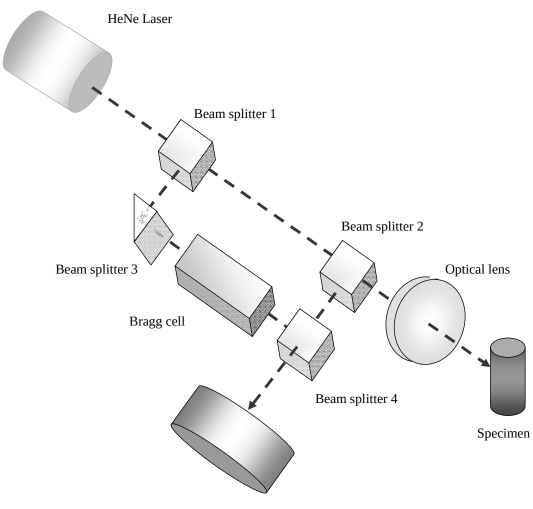

Figure 5. Principle of Laser vibrometer

III. EXPERIMENTS AND RESULTS

A. *Substrate variation and temperature storage*

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.).

The measured value d_{33} is not the actual d_{33} value. 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.

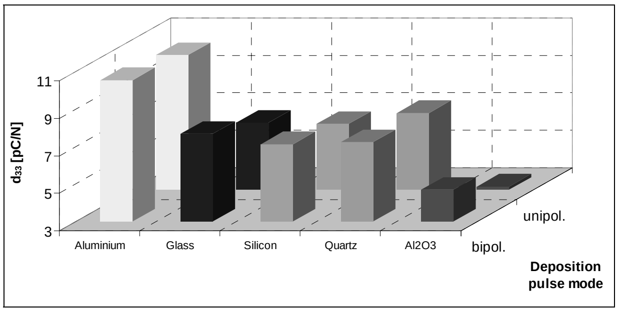

Figure 6. Results of d_{33} constants for AlN sensors deposited on different substrates

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 Poison 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 α in [10^{-6}/K]), show also lower d_{33} measurement results. This relationship can be seen in fig.6. These results are similar for both deposition processes.

Additionally the sensors 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.

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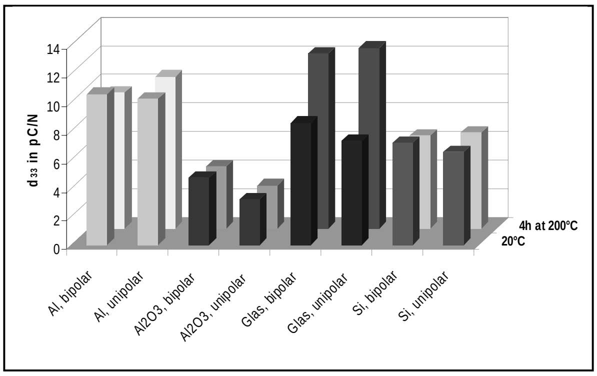

Figure 7. Piezoelectric charge constant of AlN thin film before and after temperature storage

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.

B. Laser vibration measurements

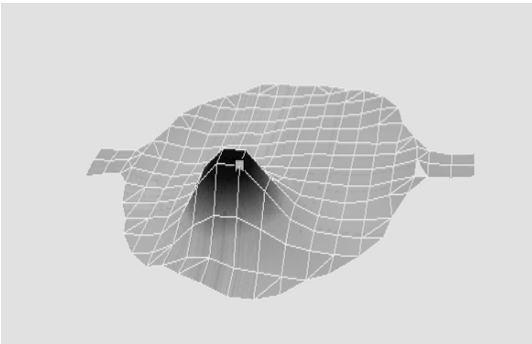

Figure 8. Vibration style of a thin film sensor at 128 MHz with max. z-warping of 11 pm

The figure 8 shows an example of the resonance behaviour of a thin film sensor at 128 MHz, which is nearly the lambda/4 vibration. A mechanical z-warping of the AlN thin film sensors by exciting with an electrical voltage could be detected with these Laser measurements.

The result shows a small displacement of the centre of warping vibrations from the sensor midpoint. The reason of this behaviour can be explained by the sensor geometry and the additional warping of the silicon substrate. This was an excellent test for investigating different sensor electrode designs and substrate materials in the future.

C. Simulation results

The influence of typical materials parameters can be calculated and the results compared to the pulse-echo measurements with the simulation of thin film layers by the MASON model. Therefore it is necessary to use the exact geometries, density, acoustic wave velocity and piezoelectric charge constants, e.g. to compare the real measurements with the simulation results. In the fig. below can be seen a simulated back wall echo signal with a silicon substrate of 500 micron thickness and a transducer geometry like mentioned above.

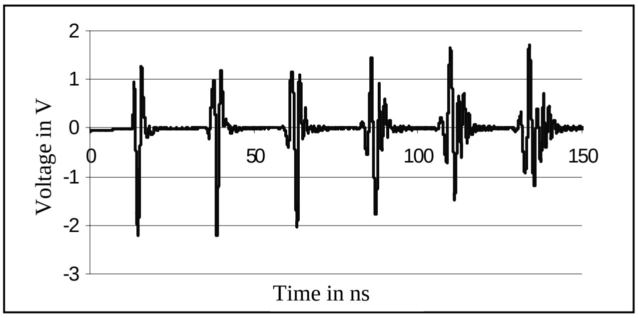

Figure 9. Simulated back wall echo from silicon substrate

D. Electrode Size Variation

The variation showed a detectable reflected ultrasound wave for all electrode sizes. Sensors with the smallest electrode size and deposited with the bipolar mode could not be used for measurements. For these sensors a misalignment of the masks caused short circuits between top electrode and ground layer.

The overview of the measured maximum signal amplitudes is shown in fig. 10. For both parameter sets the electrodes with 1 mm² 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 mm² 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.

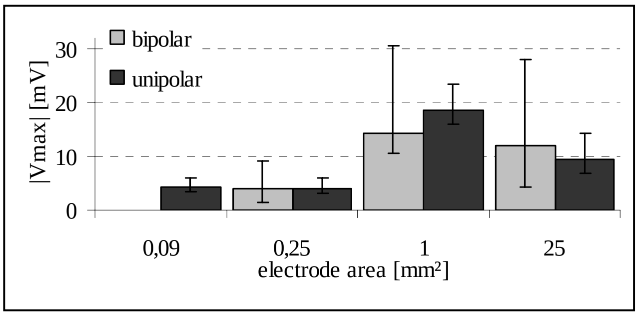

Figure 10. Maximum amplitude |Vmax| of the 4th back wall echo without additional gain for square shaped electrodes with edge lengths of 0.3mm, 0.5 mm, 1 mm and 5 mm.

The variation of the mean values for the unipolar mode is between 7.5 % for the 1 mm² electrodes and 15.6 % for the 25 mm² electrodes. The variation of the values for the bipolar mode is higher. It varies between 15.7 % for the 0.25 mm² electrodes and 21.5 % for the 25 mm² electrodes.

Fig. 11 shows the single values for the measured maximum amplitude of the different sensors for both deposition parameter sets. A dependency between maximum amplitude and sensor position on the substrate could not be found. Therefore a misalignment of the masks (e.g. offset or rotation) could not be the main reason for the higher scattering with the bipolar deposition mode.

Further there was no connection between a low amplitude and the position of the sensor that was similar on all substrates. Thus a systematic variation of the film properties or crystal structure caused by the deposition process could be excluded.

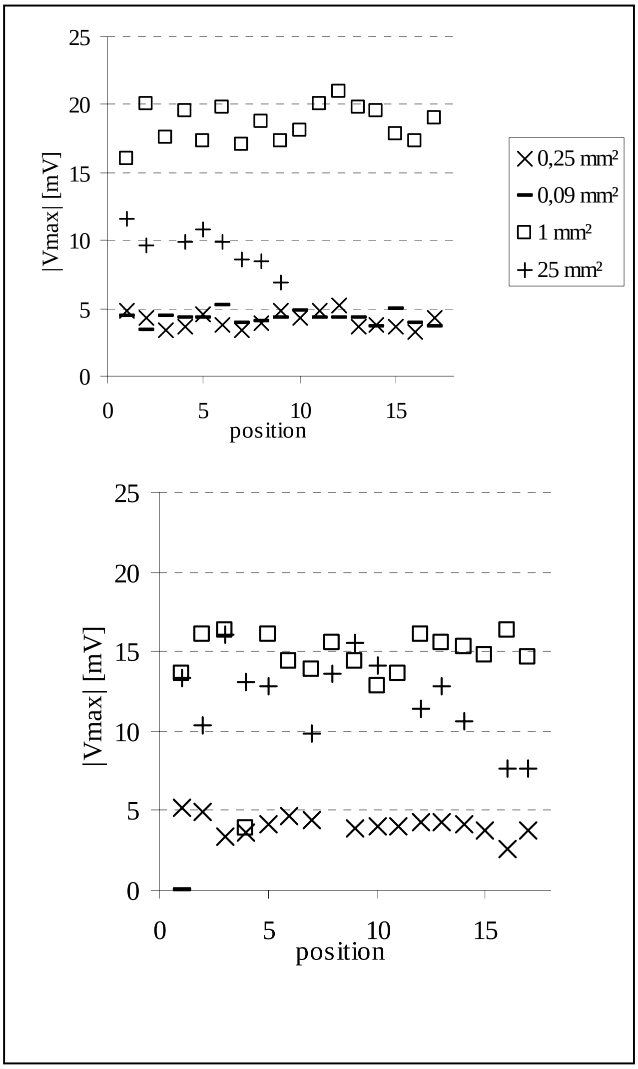

Figure 11. Maximum amplitude |Vmax| of the 4th back wall echo without additional gain for square shaped electrodes against sensor position on the silicon substrate. Each electrode area was sputtered with unipolar (top) and bipolar (bottom) deposition mode.

IV. 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 and simulations of layer thicknesses based on a MASON model have assisted the material considerations. Different substrate materials are principle usable, like e.g. silicone, aluminum oxide or quartz.

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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. Today these components were investigated with the ultrasonic microscope and mechanical scanning of single transducer during the components are placed in a liquid bath. The ultrasonic microscope is therefore very sensitive in case of delaminations, flaws, pores, cracks and gives important information about the consistence and quality of a product. The evaluations were carried out with single element transducer and frequencies from 5 MHz up to 200 MHz. The measurement time is relative long caused by the necessary mechanical scanning and the lateral resolution limited by the scanner precision. For the scanning in z-direction also a parallel use of 2 to 4 single transducers focusing in different depth are necessary. 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.

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