Double-Beam and four-point

Principles of electrical and mechanical characterization of piezoelectric thin films are discussed. Both large- and small-signal measurements are presented for AlN (aluminum nitride) and PZT (lead zirconate titanate) films. Additionally, precision aspects and tolerances are addressed for typical measurement set-ups such as in Double-Beam Laser Interferometry and four-point bending test methods. To conclude, the authors discuss possibilities of wafer level vs. single test structure characterization.

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Knowledge of the piezoelectric properties of thin-film structures on substrates is crucial for the development and design of e.g. micro-electromechanical systems (MEMS). But, test set-ups that have been established for bulk materials, can not be used for thin-film structures. Obstacles for these measurements on the one hand are very small thin-film deformations in the picometer range. On the other hand, it is a challenge to get well-defined mechanical boundary conditions for stress and strain.
For actuator and sensor applications two different ways of film excitation can be distinguished:

1. Electrical excitation of a structure to induce a deformation or vibration of the device when it is used as an actuator.
2. Mechanical excitation due to pressure or force and measurement of the electrical charge response of the device in sensor applications.

In both cases, the polarization direction and therefore the 'relevant' piezoelectric coefficient (longitudinal or transversal) needs to be taken into consideration. The transversal piezoelectric coefficient perpendicular to the polarization direction is typically used in the cantilever and membrane structures of piezoelectric MEMS devices.

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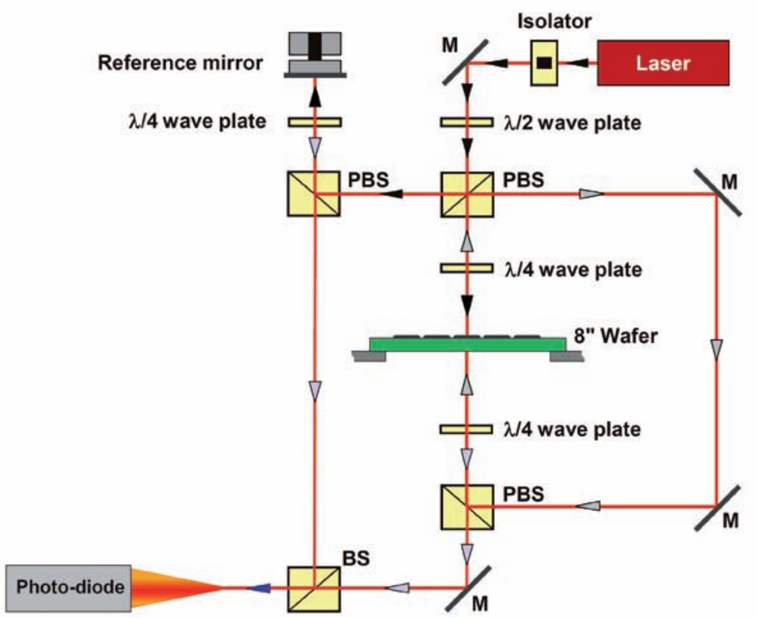

Figure 1. DBLI principle as it is used in the aixDBLI system from aixACCT.

Over the last years, new measurement methods have been developed to extract characteristics like the longitudinal $d_{33,f}$ and transversal $e_{31,f}$ piezoelectric coefficients. The suffix '33' is a reduced tensor notation and indicates that the coefficient $d_{33,f}$ correlates an electrical excitation in the polarization direction with a mechanical deformation response in the same direction. In contrast, the $e_{31,f}$ coefficient couples the generated electric charge when a film is deformed perpendicular to the polarization direction. The suffix 'f' indicates an effective value of the coefficient involved, as influenced by the properties of the substrate and electrode layers. Usually the measured effective thin-film parameters are smaller than reported bulk values due to clamping of the underlying substrate. Known measurement methods are the following:

- Measurement of the piezoelectric effect in parallel to the polarization direction (d_{33}) with a Double-Beam Laser Interferometer by applying an electrical excitation signal to the sample [1], [2].
- Measurement of the direct piezoelectric coefficients by applying a pressure on the sample and integrating the charge on the electrodes [3]. But, it has been shown by [4] that the observed high piezoelectric response is mainly influenced by substrate bending.
- Measurement of d_{31} from the bending of a cantilever structure by applying an electrical excitation signal to the film or by mechanically bending the cantilever and measuring the current response [5].

Two established measurement methods will be described in more detail. One to derive the longitudinal and the other for the transversal piezoelectric response.

Thin-film measurement principles

Measurements using Double-Beam Laser Interferometry (DBLI)

Typically the high resolution of laser interferometry is used for precise measurements of very small mechanical deformations of thin-film structures. But, unavoidable sample or wafer bending effects lead to large measurement errors. These can be extinguished by the differential measurement method used in DBLI, which is shown in principle in Figure 1. With this method thin-film expansions can be measured under electrical excitation with a resolution much better than 1 pm. This has been proven by measurements of the linear expansion of an x-cut Quartz single-crystal sample with known piezoelectric response.

Figure 2 shows example measurements of the large- and small-signal response of a 1 µm thick PZT film. One great advantage of this measurement principle is that it can be

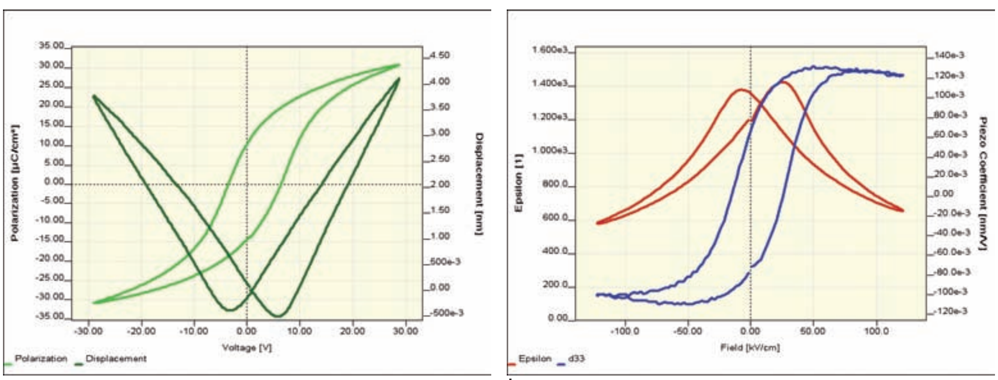

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Figure 2. PZT thin-film characterization.
(a) Large-signal polarization and displacement response.
(b) Small-signal dielectric and piezoelectric $d_{33,f}$ response vs. applied dc bias voltage.

Figure 3. The aixDBLI system for automated wafer level measurements on wafer sizes up to 200 mm.

used not only for measurements on small wafer pieces but also on whole wafers. So piezoelectric film property distributions can be measured at an early stage of the processing of the MEMS devices.

The effective piezoelectric coefficient $d_{33,f}$ describes the film response on an ideally clamping substrate. It is defined, as introduced in [4] and [6], by:

$$d_{33,f} = \frac{S_3}{E_3} = d_{33} - 2d_{31} \cdot \frac{s_{11}^E}{s_{11}^E + s_{12}^E}$$

where E_3 is the electrical field in 3-direction, S_3 the mechanical strain in 3-direction, and s_{11}, s_{12} and s_{13} are elements of the mechanical compliance matrix of the piezoelectric film; the superscript E denotes that the values are measured at constant electrical field.

Additional effects like a top-electrode-size dependency of the piezo response, [7] and [8], or changes of the coefficient across the top electrode can be investigated with DBLI and reveal important information for layout and design of applications.
Figure 3 shows the DBLI system that was constructed by aixACCT Systems, Table 1 lists technical data.

Table 1. Technical data of the aixDBLI system.

Resolution	≤ 1 pm tested by x-cut Quartz
Measurement range	5 pm to approx. 25 nm
Laser wavelength	632.8 nm

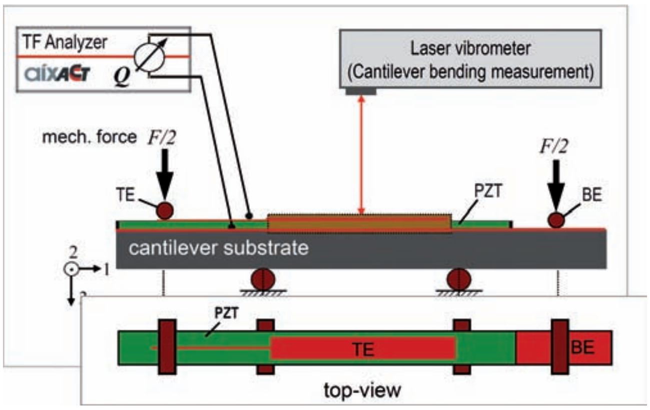

Figure 4. Measurement set-up to measure the transversal piezoelectric coefficient by the four-point bending configuration.

Four-point bending measurements

In contrast to the electrical excitation of the DBLI system, the four-point bending set-up uses a mechanical sample excitation and the electrical response is measured. Furthermore, the transversal piezoelectric response perpendicular to the film polarization direction is measured. This effect is exploited in many MEMS devices based on cantilever or membrane structures. Figures 4 and 5 show the measurement set-up and the sample holder itself, which is used to stress the cantilever bending samples. The aspect ratio of cantilever length to width should not be smaller than 8 to fulfil the requirements of a homogeneous stress distribution. This has been verified by finite-element simulations in [9]. The piezoelectric film thickness needs to be much smaller than the substrate thickness.

Figure 5. The aix4PB measurement system: four-point bending sample holder with connected single-beam laser interferometer.

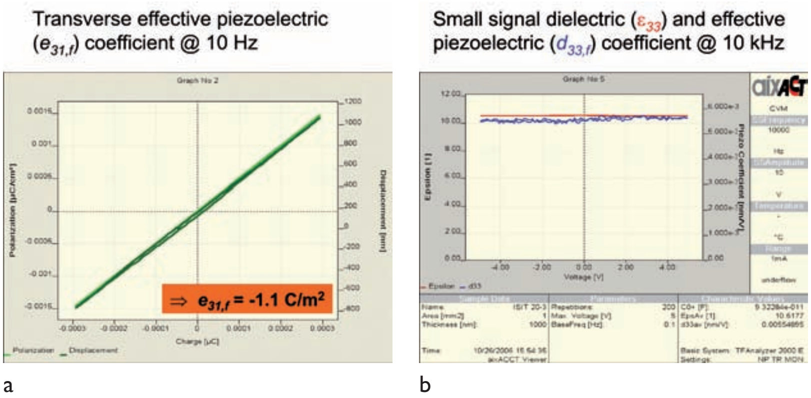

Figure 6: Piezoelectric response of an AlN thin film of 1 μm thickness.
(a) Transversal (by using the aix4PB measurement system).
(b) Longitudinal.

Under these conditions this four-point bending configuration guarantees a very homogeneous and well-defined tensile stress distribution in the piezoelectric thin film. These well-defined mechanical boundary conditions are most important for precise measurements and a drawback for many other measurement methods for $e_{31,f}$. The effective transversal piezoelectric coefficient $e_{31,f}$ is defined, according to [5] and [6], as:

$$e_{31,f} = e_{31} + e_{33} \cdot \frac{s_{13}^E}{s_{11}^E + s_{12}^E} = \frac{d_{31}}{s_{11}^E + s_{12}^E}$$

Between the inner two supports of the four-point bending set-up the sample is exposed to a constant bending moment and therefore the thin film is exposed to a constant mechanical strain. This strain induces electrical charges on the electrodes proportional to the direct piezoelectric effect. An equation for $e_{31,f}$ can be derived that is only dependent on the bending of the cantilever (which is measured with the laser interferometer), the measured charge, and material coefficients and geometrical dimensions of the cantilever. A measurement repeatability of less than one percent can be achieved. More details on this measurement method can be found in [9].

Figure 6 shows the transversal and longitudinal piezoelectric response of an AlN thin film. The transversal response was measured using the four-point bending (4PB) configuration, the longitudinal response was derived using DBLI.

Device characterization on wafer level

It is most desirable in the production of piezoelectric MEMS devices to fully determine the electromechanical properties of the piezoelectric film at an early processing stage after the deposition of the film. So that only wafers with good film quality are further processed with cost- and time-consuming steps like backside etching.

For MEMS devices based on the longitudinal piezoelectric coefficient all relevant data can be directly measured on wafer level with the aixDBLI system. This can be done right after deposition and structuring of the piezoelectric film and the electrodes. Information like the values of $d_{33,f}$, the dielectric coefficient and loss tangent, the maximum obtainable strain, and the leakage current through the film

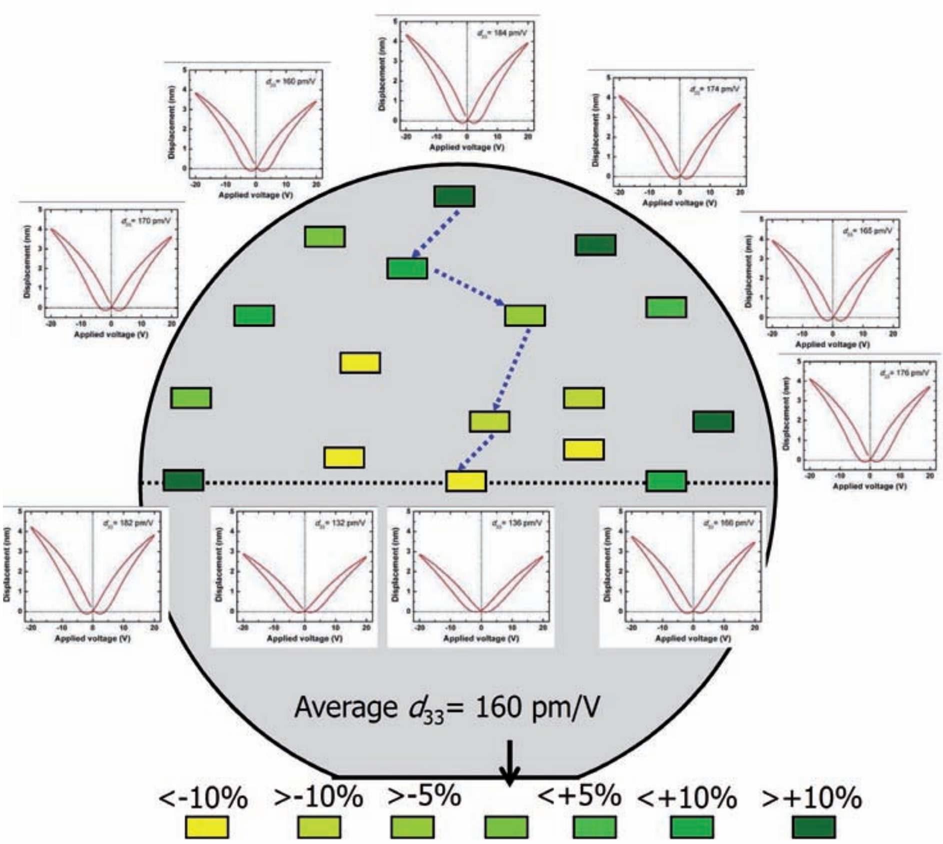

Figure 7. Wafer distribution of the large-signal displacement and derived average effective longitudinal piezo response of a PZT thin film (by courtesy of SolMateS).

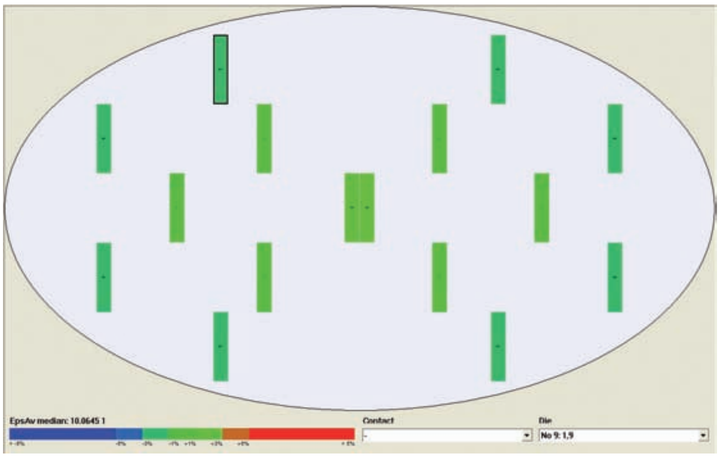

Figure 8. Wafer distribution of the dielectric constant of an AlN thin film deposited on a 150 mm wafer.

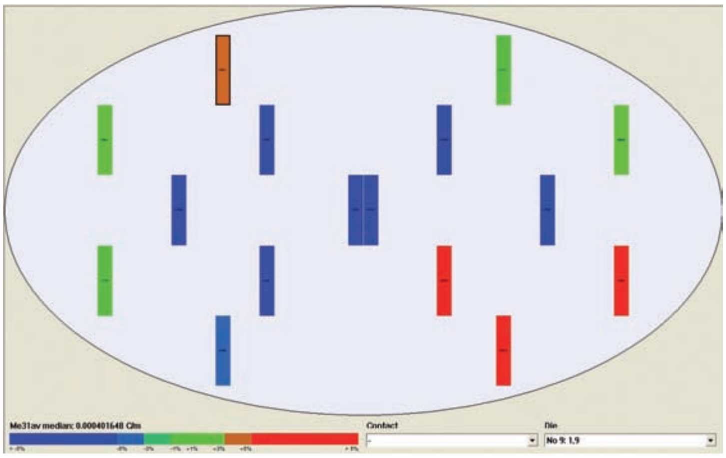

Figure 9. Wafer distribution of the transversal piezoelectric response of an AlN thin film deposited on a 150 mm wafer. Measured on bending structures cut from different positions on the wafer.

(extracted from the polarization loop) provide criteria to decide to further process the wafer. Furthermore, fatigue tests on selected devices or test structures help to optimize the processing. An example of such a wafer map distribution of the large-signal displacement on a 150 mm PZT wafer is given in Figure 7.

As discussed before, measurements of the transversal piezoelectric coefficient $e_{31,f}$ can not be done directly on wafer level. But, for dense and homogeneous films there exists a direct correlation between $d_{33,f}$ and $e_{31,f}$. So, a process control for MEMS devices based on this effect is as follows: during material qualification the cantilever test structure is part of the wafer design and will be fully characterized after the wafer has been cut. Wafer map distributions of the dielectric constant and the transversal piezoelectric response of an AlN thin film (provided by Fraunhofer ISIT, Itzehoe, Germany) are shown in Figures 8 and 9. Criteria can now be fixed for $d_{33,f}$, dielectric constant, and loss tangent that correlate to a minimum specified $e_{31,f}$ value. During production these values are used for the wafer level test with the aixDBLI system as described above, which does not require this special cantilever test structure and the cutting of the wafer.

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