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Vertical displacement detection of an aluminum nitride piezoelectric thin film using capacitance measurements

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Piezoelectric materials have a strong interaction between their mechanical and electrical properties that translates into innovative components and circuits architectures. This work describes an original method using the electromechanical properties of the aluminum nitride (AlN) piezoelectric material to characterize its vertical extension when an electric field is applied. The novel techniques based on measurements of a planar parallel plate AlN capacitor without and with bias employing an impedance analyzer. The parallel plate capacitor theory and piezoelectric material analysis are used to calculate the vertical displacement of the AlN film.

Keywords: Aluminum nitride, Characterizations, Material parameters, Piezoelectric material

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I. INTRODUCTION

Piezoelectric materials have become very useful in MEMS devices because of their electrical–mechanical reciprocity. MEMS merge the functions of sensing and actuating with computation and communication to locally control physical parameters. Piezoelectric materials are capable of very high energy and power densities at micro scales [1]. The high frequency of operation inherent in MEMS devices matches well with the relatively high-frequency capability of piezoelectric materials. The most commonly used piezo-materials in MEMS devices are lead zirconate titanate (PZT), zinc oxide (ZnO), and aluminum nitride (AlN). AlN has attracted considerable attention in recent years owing to its unique properties. Specifically, its high thermal conductivity, moderate piezoelectricity, low dielectric and acoustic losses, and high acoustic wave velocity have made highly textured AlN thin films a prime candidate for electro-acoustic applications such as filters, resonators, and sensors. Further, its chemical stability as well as compatibility with IC processing makes AlN thin films a competitive alternative to single crystalline piezoelectric substrates for microwave applications. A comparison between various piezoelectric materials is summarized in Table 1.

Therefore, it has become increasingly important to characterize the activity of piezoelectric materials under conditions relevant to such applications. Consequently, different methods have been sought to measure the piezoelectric activity. Table 2 summarizes the different methods that are presently used to extract or to measure the activity of a piezoelectric material. Nevertheless, these techniques have been acknowledged by the scientific community; their results still need further understanding and validation. The use of mechanical devices looks a quick and easy solution. However, the need for high precision poses a problem. Direct measurement of induced charge becomes problematic for thin films because of the properties of metallic contacts used to apply the force and to collect the piezoelectric charges. The resonance techniques are based on the assumption that samples are infinitely thin or infinitely long, and the corrections for finite dimensions must be taken into account. Moreover, the relationship of resonant and anti-resonant frequencies to the piezoelectric and elastic properties of films becomes less certain. In optical techniques the sample is constrained by the substrate whose eventual deformation by the applied field must be considered.

Recently, we have presented in [8] a promising method of measuring the vertical extension of a piezoelectric thin film using an impedance analyzer. It does this by taking the ratio of parallel plate capacitance for two different bias conditions under a set of assumptions in deriving equations for the ratio

Table 1. Comparison between various piezoelectric materials.

Property	PZT	ZnO	AlN
d_{33}	High	Moderate	Low
d_{31}	High	Moderate	Low
Resistance	High	High	High
Constant	Huge	High	Low
RF losses	High	Moderate	Low
Sound velocity	Slow	Slow	High
Acoustic losses	High	Moderate	Low
TEC	High	High	Low
GHz capability	Poor	Poor	Good
Ferroelectricity	Yes	Yes	No
Environment	Unfriendly		Friendly
Density	High		Low
CMOS compatiable	Not	Not fully	Fully

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Table 2. Concepts for piezoelectric characterization.

Method	Type	Physical effect	Ref.
Laser	Optical	Bias-displacement	[2]
cantilever	Mechanical	Force-charge	[3]
Wafer	Mechanical	Force-charge	[4]
Loading	Mechanical	Force-charge	[5]
Resonant	Electrical	Resonant frequency	[6]
AFM	Mechanical	Bias-displacement	[7]

of capacitance for the two bias conditions. In this work, the determination of AlN thin-film displacement is proposed and described. The technique relies on using the impedance analyzer (or network analyzer) to measure the capacitance voltage dependence of AlN composite structure. The developed analytical model is used to extract the vertical extension of the film material. For validation, finite-element analysis is performed.

II. THEORY AND ANALYSIS

The capacitance of a dielectric film is given by the equation [9]:

$$C_o = \frac{\epsilon_0 \epsilon A}{d}, \tag{1}$$

where ϵ_o is the permittivity of vacuum, ϵ is the relative permittivity or dielectric constant, d is the thickness of the film, and A is the area of the capacitor. Having measured the capacitance of an AlN film, (1) can be used to find the electronic dielectric constant. At room temperature the piezoelectric AlN thin film material does not exhibit tunability of its dielectric constant when a dc bias field is applied. Further, AlN does not require any polling process due to its oriented structure. Figure 1(a) shows a solid circular piece of an AlN piezoelectric material. When the circular solid is driven with the application of a dc field E (Fig. 1(b)), it will cause its material domains to contract; therefore, the thickness of the film increases by Δd, while the area decreases by ΔA [10]. The modification in the material shape is translated into a change in the capacitance value, which is approximately calculated through the well-known capacitance parallel plate formula:

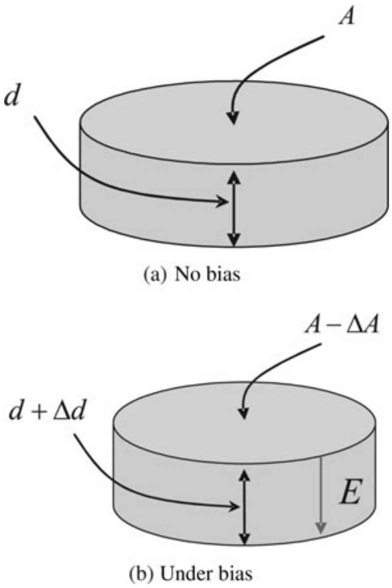

Fig. 1. AlN piezoelectric response to applied field. d_{31} is perpendicular to the cylindrical surface aligned with the direction of the applied field and d_{33} is parallel to the surface.

$$C_V = \epsilon_0 \epsilon \frac{(A - \Delta A)}{(d + \Delta d)}, \tag{2}$$

where both the vertical extension of the AlN material Δd, and the variation in area ΔA are correlated with the magnitudes of both the longitudinal d_{33} and the transverse d_{31} charge constants as follows [11]:

$$\Delta d = V|d_{33}|, \tag{3}$$

$$\Delta A = V|d_{31}|A/d. \tag{4}$$

Moreover, it is well known that the magnitude of the d_{33} coefficient of the PZT is about twice the d_{31} [11]; therefore,

$$|d_{33}| = 2 \times |d_{31}|. \tag{5}$$

Thus,

$$\frac{\Delta d}{d} \approx 2 \frac{\Delta A}{A}. \tag{6}$$

Rewrite (2) as follows:

$$C_V = \epsilon_0 \epsilon \frac{A\,(1 - (\Delta A/A))}{d\,(1 + (\Delta d/d))}. \tag{7}$$

Hence,

$$C_V = C_o \frac{(1 - (\Delta A/A))}{(1 + (\Delta d/d))} \tag{8}$$

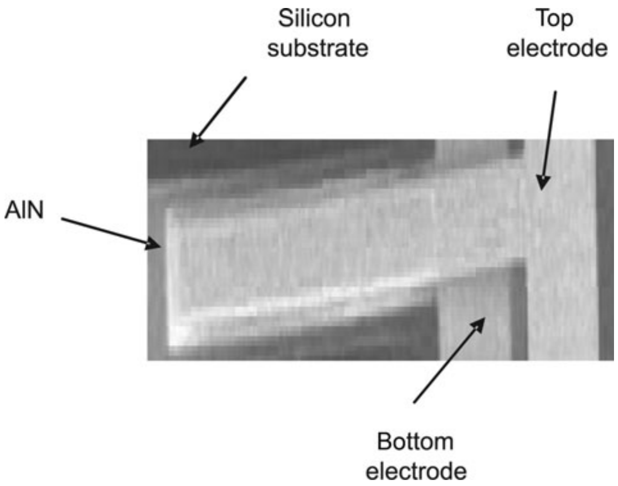

Fig. 2. Fabricated AlN parallel plate capacitor. The surface of the silicon substrate represent the xy plane, where the z-axis is perpendicular to the substrate.

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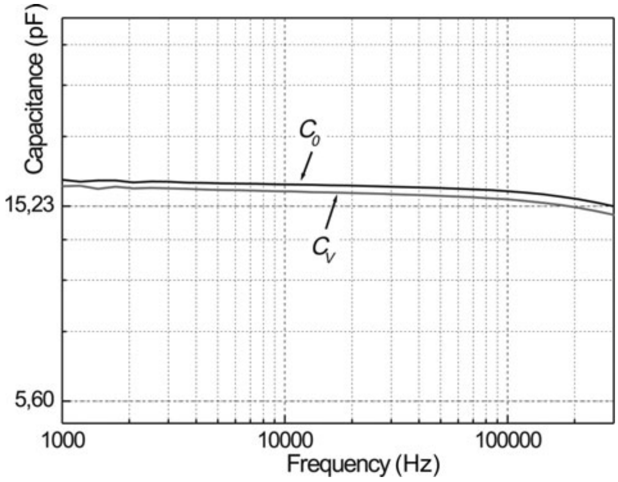

Fig. 3. AlN capacitance versus frequency (logarithmic scale): C_o is the unbiased capacitance and C_V is the capacitance with the application of 2 V.

Inserting (6) into (8) and solving for Δd yields:

$$\Delta d = d\left(\frac{1 - C_r}{0.5 + C_r}\right), \tag{9}$$

where C_r is the ratio between C_V and C_o.

The piezoelectric material is activated with the application of dc field and the capacitance will decrease due to the change in the geometrical dimensions as predicted by (3) and (4). Hence, knowing the thin film thickness and capacitance ratio will enable the vertical extension of the piezoelectric material to be determined.

III. MEASUREMENTS AND ANALYSIS

A parallel plate capacitor composite of AlN piezoelectric material has been fabricated and is shown in Fig. 2. The capacitor dielectric material is composed of AlN thin film of thickness 0.6 μm. The electrodes are made from Molybdenum with a thickness of 0.1 μm. The capacitor has an area of 700 × 200 μm^2. The capacitances of the fabricated device with and without dc bias were measured with the HP4294A impedance analyzer and are shown in Fig. 3. The measurements show a stable and smooth behavior over the frequency. These results represent first experimental evidence of the theory presented above. That is, applying a dc bias yields the expansion of the material due to the converse piezoelectric effect. This causes a decrease in the capacitance yielded by this structure as clearly depicted in Fig. 3. The amount of variation in capacitance due to the application of dc bias is around 3.5% from its unbiased value.

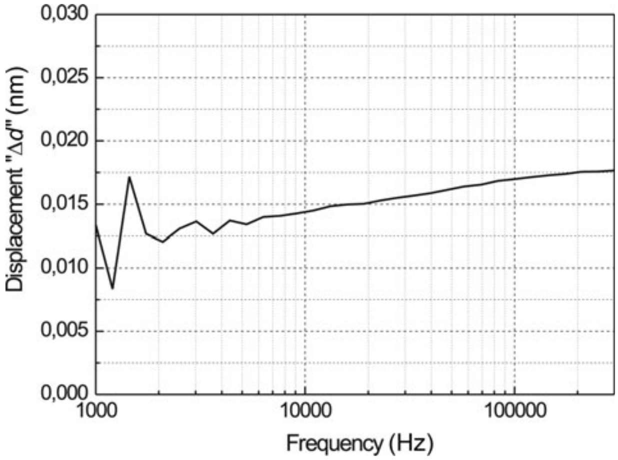

Fig. 4. Relationship between driving frequency and piezoelectric displacement.

Table 3. Material parameters.

Material parameter	Value
Young's modulus	80 (GPa)
Poisson ratio	0.22
Piezoelectric coefficient	5.7 (pm/v)

From (9) and the data of Fig. 3, the displacements of the piezoelectric material values as a function of the driven frequency are computed and are shown in Fig. 4. Δd shows non-stable behavior up to 2 kHz due to measurement setup that use long cables, and then becomes more stable up to 300 kHz. The value of Δd changes from 12.5 to 17.5 pm.

IV. FEM ANALYSIS AND VALIDATION

The AlN material tested in this work has been measured and the results of the mechanical and electrical properties are listed in Table 3. Numerical simulations based on the finite-element method (FEM) using the piezoelectric analysis engine from CoventorWare [12] have been performed and the results are shown in Fig. 5. The simulations reveal that the vertical extension of the AlN material is homogeneously

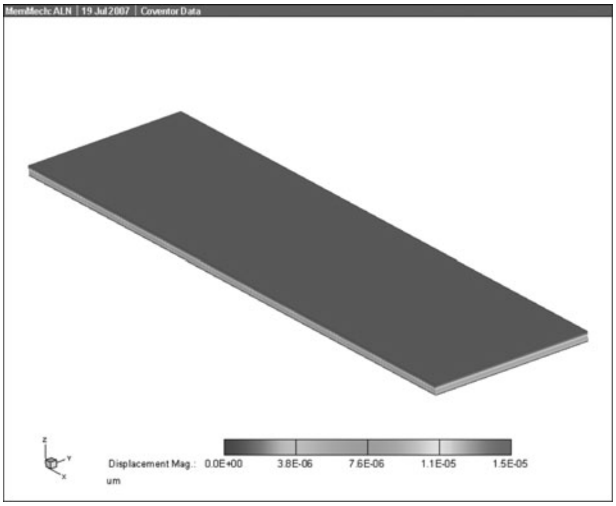

Fig. 5. Simulated vertical displacement of the AlN capacitor using FE analysis.

distributed around 15 pm. The results obtained by the proposed experimental approach and the numerical model show excellent agreement with each other. Considering the simplicity of the introduced method and the difficulty of the task, this represents a very satisfactory and promising approach.

V. CONCLUSION

An original method for the extraction of the vertical extension of AlN piezoelectric material under dc bias is presented. The presented approach does not impose constraints or limiting conditions. The method described here is also valid for other arbitrary piezoelectric materials, but only for piezoelectric ones that are not ferroelectric. As a matter of fact, the technique circumvents complicated preparation and uses arbitrary sample geometry. It may be used to determine the piezoelectric vertical extension for films with a thickness ranging from several nanometers up to several hundreds of micrometers.

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Mahmoud Al Ahmad was born in Jenin, West Bank, in 1976. He received his BA. degree in electrical engineering from Birzeit University, Ramallah, Palestine, in 1999 and both the M.Sc. and the Dr.-Ing. degrees in microwave engineering from Technische Universitaet Mnuechen, Munich, Germany, in 2002 and 2006, respectively. Dr. Al Ahmad was working at Siemens Corporate Technology/Munich towards his Ph.D. degree involving the design and fabrication of wide tunable passive microwave components for Software Defined Radio, combining two ceramic technologies: low-temperature co-fired ceramics (LTCC) and piezoelectric actuation (PZT) technologies. In 2005 he joined the Institut d'Electronique de Microélectonique et de Nanotechnologie (IEMN) at Lille/France with a post doc. fellowship. He has been engaged in barium strontium titanate tunable capacitor loss compensation using active negative circuit techniques. Since September 2006 he has been working as a research scientist at the Laboratoire d'Analyse et d'Architectures des Systèmes at the Centre National de la Recherche Scientifique (LAAS-CNRS) in Toulouse, France. Currently, his work involves the design and fabrication of tunable active/passive microwave components for the next wireless generations. His research interests include the design and fabrication of integrated millimeter-wave and microwave circuits based on barium strontium titanate (BST), piezoelectric material (PZT), ferromagnetic material (LSMO) thin films and carbon nanotubes/nanowires technologies. Moreover, he is engaged in the characterization of bulk and thin material characterization for microwave applications employing microwave techniques. He is also a member of the IEEE Microwave Theory and Techniques Society.

Robert Plana was born on March 1964 in Toulouse. He obtained his Ph.D. in 1993 at LAAS-CNRS and Paul Sabatier University on the Noise Modeling and Characterization of Advanced Microwave Devices, (HEMT, PHEMT and HBT) that includes reliability. In 1993, as an associate professor at LAAS-CNRS, he started a new research area concerning the investigation of millimeter-wave capabilities of silicon as based technologies. More precisely, he has focused on the microwave and millimeter-wave properties of SiGe devices and their capabilities for low-noise circuits. In 1995, he started a new project concerning improvement of the passives on silicon through the use of MEMS technologies. In 1999, he was involved with SiGe semi-conductor in Ottawa, where he was working on the low-power and low-noise integrated circuits for RF applications. In the same year, he received a special award from CNRS for his work on silicon-based technologies for millimeterwave communications. In 2000, he was made professor at the Paul Sabatier University and Institut Universitaire de France and then started a research team at LAAS-CNRS in the field of Micro and Nanosystems for RF and millimeter-wave communications. This main interests are the technology, design, modeling, test, characterization and reliability of RF MEMS for low-noise and high-power millimeterwave applications and the development of the MEMS IC concept for smart microsystem. He has built a network of excellence in Europe in the field 'AMICOM', regrouping 25 research groups. He has authored and co-authored more than 200 international journals and conferences. In 2004, he was appointed as Deputy Director of The Information and Communication Department at the CNRS Headquarters. From January 2005 to January 2006, he was appointed Director of the Information and Communication Department at CNRS. He is now heading a research group at LAAS-CNRS in the field of micro and nanosystems for wireless communications.