A New Standard for Thin Film Actuators with Sol-gel PZT

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Abstract

The actuator of the XAAR 5601 GS3 printhead is based on thin film PZT deposited by the sol-gel technique. To meet the required printhead performance, the PZT should be as good as or better than the best-known sputtered PNZT films. This objective was achieved through a systematic investigation of sol-gel PZT films including the effect on all critical PZT properties of pyrolysis and crystallization conditions, lead excess, the nature of dopants and their concentration and distribution. The outcome is presented in this paper.

Integration of piezoelectric thin films, and in particular lead zirconate titanate (PZT) thin films, into standard MEMS technology is an active area of research that focuses on applications such as inkjet and other actuators, sensors, and adaptive optics [1-4]. There are two major techniques for deposition of relatively thick PZT films, of 1 - 3 µm: sputtering and sol-gel. Despite extensive research over more than a decade, the performance of PZT thin films remains lagging behind their bulk counterparts. Recently, impressive performance of sputtered Nb-doped PZT thin films has been reported [5-7]. At the same time, not much advancement has been reported for sol-gel films.

To deliver printheads that have a steady performance in an industrial environment over a span of a few years and at low operating voltage, PZT thin films for inkjet actuators must meet many stringent property requirements. These include a long lifetime, minimal degradation even after 10^{11} cycles, high dielectric breakdown strength, low leakage current, high piezoelectric coefficients (in case of the d_{31} - operating mode, the d_{31} value should exceed 200 pm/V, but even preferably exceed 250 pm/V). Note that some of these properties depend on both the piezoceramic material and the actuator design. Because of the significance of the latter, the majority of our characterization activities were performed with real devices.

Figure 1 depicts the schematic representation of the cross-section of our actuator. There are five major layers that conventional actuators include: a diaphragm (or membrane), bottom electrode, PZT film, top electrode, and a passivation / insulating layer (the passivation layer may not cover the entire top electrode, shown is partial coverage). Every layer is important and needs to be taken care of properly; in this paper, however, we focus on the PZT layer, and not on the electrodes and interfaces between them and the PZT layer.

The PZT films were made by spin-coating commercial 15 wt% PZT-E1 sol-gel solution (Mitsubishi Materials Corporation) on platinized silicon substrates. After each deposition of sol-gel solution, the wafer went through a pyrolysis step, following which pyrolyzed amorphous layers were either individually crystallized or in pairs in a rapid thermal annealer (RTA). Typical deposition conditions were the following: spinning at 3000 rpm for 45 sec; pyrolysis at 100°C for 1 min and 300°C for 4 min; crystallization in an RTA at 700°C for 1 min. It is known that the actuator performance is enhanced if the PZT orientation is predominantly {100} [1,2]. PZT film orientation depends solely on the orientation of the first portion of the PZT film, the so called seed layer, which is adjacent to the platinum bottom electrode. Thus, special attention was devoted to the optimization of both the composition of the sol-gel solution for this layer – lead excess and Ti/Zr ratio were controlled – and its deposition conditions (mainly the conditions of spinning and pyrolysis).

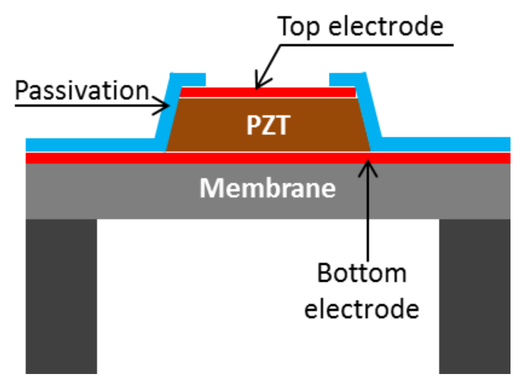

***Figure 1.** Schematic representation of the cross-section of the actuator.*

The phase purity, crystallographic texture, and grain morphology of the PZT were examined with X-ray diffraction (XRD) and field emission scanning electron microscopy (FE-SEM). Dielectric breakdown strength was measured over incremental steps of 1V with a 2 sec hold time for each step. The final films showed a high degree of {100} orientation (Lotgering factor > 0.98), large grains (average size > 200 nm) and a very smooth surface (RMS surface roughness < 1.3 nm). The films exhibited a dielectric breakdown strength ≥ 1 MV/cm, which is comparable with, or even better than, the dielectric breakdown strength of a well-prepared, sputtered PZT film.

The effective, transverse, piezoelectric coefficient, $e_{31,f}$, was measured by different methods since it is impossible to exclude the effect of the substrate. The small signal $e_{31,f}$ values were obtained from the four point bending method, the cantilever method, and the DBLI (double beam laser interferometer) method; and all agreed remarkably well. Similarly, there was a good agreement between the large signal values from the cantilever method and the DBLI method [8]. After the measurement of transverse piezoelectric coefficients by the above standard techniques, we also performed finite element modelling of the actuator displacement and correlated the modelling results with the measured displacement. Since all the tested actuators had the same layers and dimensions, the measured displacement could be directly used to estimate the efficiency of the PZT film – in terms of its d_{31} value - using the modelling results. To minimize the effect of wafer processing on the performance of PZT, we performed the displacement measurement on the final films that were used to build printheads. To perform such measurements efficiently, precisely and reproducibly, a customized tool, through nozzle testing (TNT), was built by AixACCT. Figure 2 shows the schematic of the measurement and the displacement data for the entire die with 1420 nozzles measured semi-automatically (automatically for every individual row of nozzles). The membrane displacement after poling of the PZT and at printhead operating conditions corresponded to a d_{31} value of around 260 pm/V, which is the highest value measured for thin, piezoelectric films deposited by either sol-gel or sputtering, as shown in Figure 3.

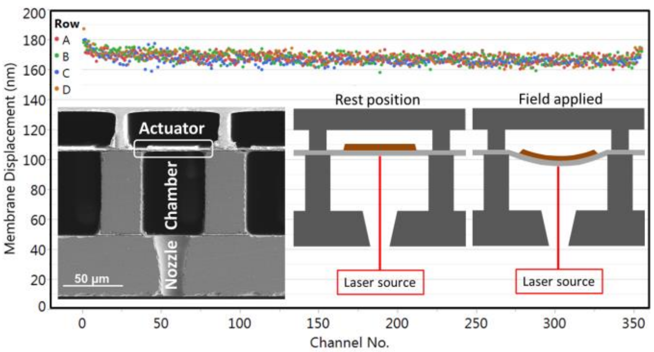

Figure 2. *Example of measurements of the membrane displacement by channel number using AixACCT's TNT tool. Measured was at 100 kV/cm, over 1420 channels total. The insert shows the cross section of a single actuator, including chamber and nozzle, and schematic of displacement measurements by 5 µm laser beam through the nozzle.*

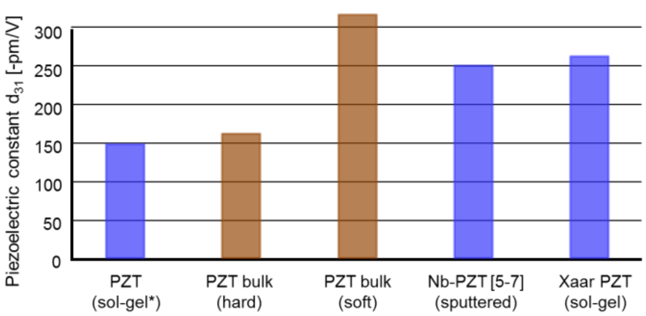

Figure 3. *Comparison of the piezoelectric coefficient, d_{31}, of various bulk and thin film PZT. Note: Bulk d_{31} is typically obtained from a small-signal resonance measurement at low electric fields whereas thin film d_{31} is derived from a large signal displacement under high electric fields. Hence while the comparison between different thin film samples is quite valid, comparison between bulk and thin film requires further attention. *) In patent literature values up to 200 pm/V have been reported.*

A special setup was developed to test PZT degradation vs. number of actuations. Up to 60 actuators were activated using a customized waveform (100 kHz, unipolar trapezoid waveform with voltage and slew rate identical to jetting conditions). The capacitance was continuously screened and at intervals the membrane displacement was also measured. For optimized PZT the drift of displacement after 1.5 x 10^{11} cycles was below 2%.

Highly accelerated lifetime testing (HALT) at both static (under DC) and dynamic (under high frequency unipolar pulse actuation) conditions was used to determine the median lifetime of the device at elevated temperatures and applied voltages, as well as the activation energy (Ea) and voltage acceleration factor (N) using the Prokopowicz and Vaskas empirical equation. The median lifetime (t_{50}), at which half of the devices from a given wafer failed, was obtained.

Figure 4 shows HALT data (failure probability vs. time) of different sol-gel PZT films under DC bias and temperature stress. The initial sol-gel PZT film, prior to the PZT development efforts, had a very short lifetime at 200°C and 300 kV/cm; t_{50} was around 0.2 hr with a noticeable number of earlier failures. The "current default" PZT film had a lifetime approximately 100 times longer, and "in development" PZT films demonstrated even better lifetime, with t_{50} close to 70 hr. It should be pointed out that sol-gel PZT based actuators, stressed up to 200°C with electric fields exceeding the operating voltage more than 3 times, exhibited superior performance, surpassing the lifetime of any published, thin film PZT.

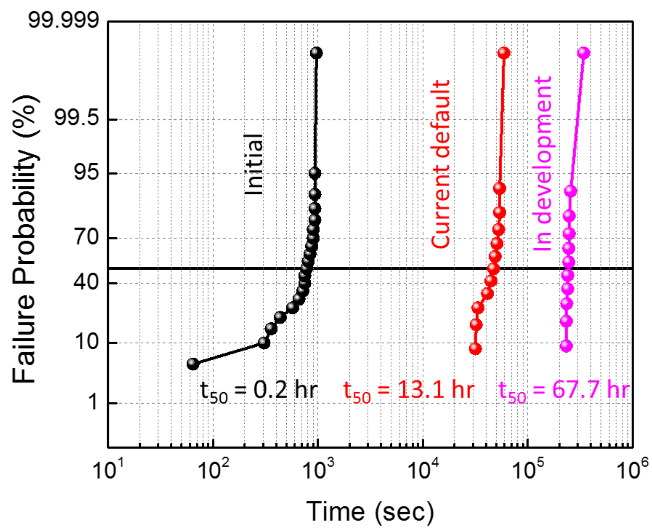

Figure 4. *Comparison of the failure probability vs. time for sol-gel PZT films on different stages of development. Test performed at 200°C and applied DC field of 300 kV/cm.*

Additionally, the samples were measured under different HALT temperature and voltage conditions. For devices made with a "current default" PZT film, three tests were conducted at a constant temperature at different voltages, and three tests at a constant voltage with varied temperature, shown in Figure 5. This set of data allowed us to estimate the activation energy for failure, which was around 1.1 eV, and the voltage acceleration factor, which was around 4.24 [9].

The performance of our sol-gel PZT, $e_{31,f}$, displacement and t_{50} were independently confirmed by measurements at AixACCT.

The long lifetime (high reliability), high dielectric breakdown strength and high piezoelectric response are attributed to the defect-free seed layer [9], excess Pb content optimization [10], presence of dopants, their distribution, electrode engineering, and so on. The printheads built with such sol-gel deposited PZT films demonstrated robust performance in wet-life testing at operating conditions. The

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actuators were able to jet more than 3000 liters per single printhead (116 mm printed width) without a significant drop in drive voltage. This correspond to ~ 2 x 10^{11} cycles for every individual actuator.

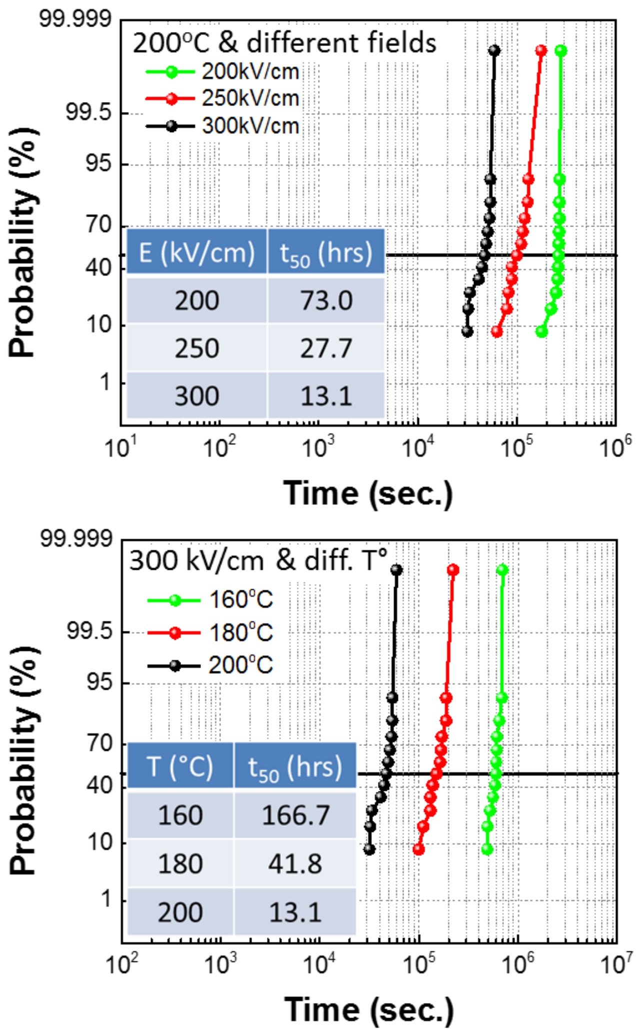

Figure 5. *HALT data at constant temperature for different fields and at constant field at different temperatures of "current default" sol-gel PZT thin films.*

Thus, the unique testing capabilities, modeling expertise, and partnerships with leading academic and industrial experts have led to improvements in the performance of sol-gel PZT to the level that allowed us to break through traditional limitations of sol-gel PZT and to deliver an adequate actuator for the XAAR 5601 GS3 printhead.

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Author Biography

Peter Mardilovich received his PhD in Physical Chemistry from the National Academy of Sciences of Belarus and is currently Chief Engineer at XAAR in Cambridge, UK. Prior to joining XAAR, he was Senior Technologist at Hewlett-Packard within the Imaging and Printing division. He holds 104 granted US patents and is the author of more than 100 papers.