Influence of silicon orientation and cantilever undercut on the determination of Young's modulus of pulsed laser deposited PZT

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In this work we show for the first time that the effective in-plane Young's modulus of $PbZr_{0.52}Ti_{0.48}O_3$ (PZT) thin films, deposited by pulsed laser deposition (PLD) on dedicated single crystal silicon cantilevers, is independent of the in-plane orientation of cantilevers.

PZT films can be grown epitaxially on silicon by PLD [1] and high quality films with bulk piezoelectric coefficients can be obtained. The epitaxial growth might lead to in-plane anisotropy in the Young's modulus of the PZT thin films [2], which can be investigated by growth on single crystal silicon cantilevers oriented along the <110> and <100> silicon crystal orientation. Deposition of PZT thin films on cantilevers affects their flexural rigidity and increases their mass, which results in a change in the resonance frequency. From the shift in the resonance frequency of the cantilevers, measured both before and after the deposition, the Young's modulus of PZT can be calculated.

We took extra care to eliminate the errors in the determination of the Young's modulus of the PZT film, by accurately determining the dimensions of the cantilevers and measuring many cantilevers with different lengths. At this precision, conventional analytical expressions [3,4,5] to calculate resonance frequencies of cantilevers might not be accurate enough, and were checked by finite element calculations. For silicon cantilevers without PZT, aligned in the <110> and <100> crystal directions, the analytical values of the resonance frequencies calculated using a plate modulus $E/(1-\nu^2)$ agree with the FEM simulations to within 0.04 % for the <110> direction, but deviate by as much as 3% for the <100> direction.

To measure resonance frequencies in the <110> and <100> directions, cantilevers were fabricated oriented parallel to the <110> and <100> directions of the silicon crystal lattice, see Fig 1 (a). To ensure precise control of the dimensions of the cantilevers, we fabricated our 3 µm thick silicon cantilevers in a dedicated SOI/MEMS fabrication process. The fabricated cantilevers vary in length from 250 µm to 350 µm in steps of 10 µm. The DRIE process used for the release of cantilevers from the handle wafer introduces an undercut in the cantilevers. This undercut is caused by over-etching as shown in Fig 1 (b) and increases the effective length of the cantilevers. Since undercut cannot be avoided, the effective length is determined by least square fitting of the measured resonance frequencies for cantilevers with a wide range of lengths [6].

Buffer layers of Yttria-Stabilized Zirconia and $SrRuO_3$, each 10 nm thick, were deposited by PLD on the cantilevers. These layers ensured that a high quality 100 nm PZT film could be grown epitaxially on the silicon. The Young's modulus of the deposited PZT thin film was determined by measuring the resonance frequencies both before and after the deposition of the PZT thin films, see Fig 2. Fig 3 shows that the resonance frequency of the cantilevers as a function of length follows a linear relation, as expected. A thorough error analysis was performed to calculate the propagation of errors to the calculated value of the Young's modulus of PZT.

The effective Young's modulus of PZT deposited by PLD was identical for both the <110> and <100> aligned cantilevers and has a mean value of 103 GPa with a standard error of ± 2 GPa,. This value is in the same order as values quoted in literature for sol-gel [7] and sputter deposited [8] PZT. This method of determining the effective Young's modulus of PZT thin films, using the effective length and appropriate effective Young's modulus for silicon cantilevers, is applicable to any thin film that can be deposited on cantilevers.

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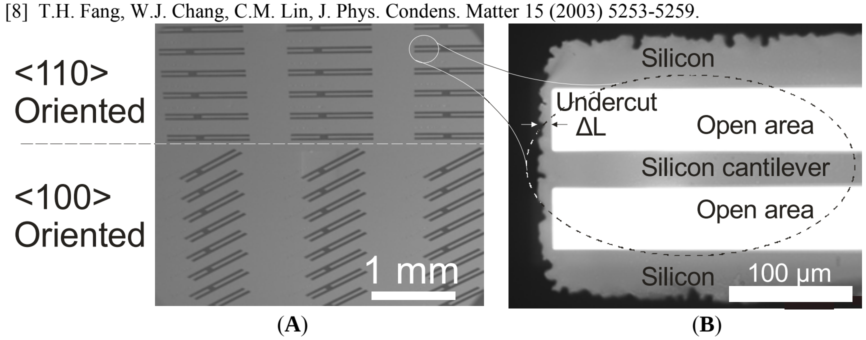

Figure 1. (**A**) Scanning electron micrographs of fabricated cantilevers. The cantilevers are aligned parallel to the <110> and <100> crystal orientations of silicon. (**B**) The length of a cantilever is increased by the effective undercut length, which depends on the nominal undercut length ΔL.

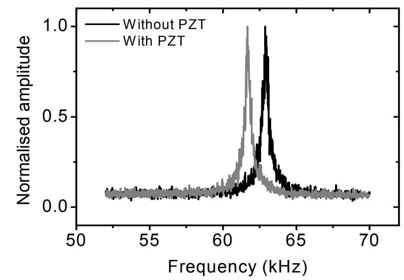

Figure 2. Measured resonance frequency before and after the deposition of PZT. The amplitude is normalised to the maximum value. The resonance frequency with PZT is lower than for the cantilevers without PZT, which is as expected.

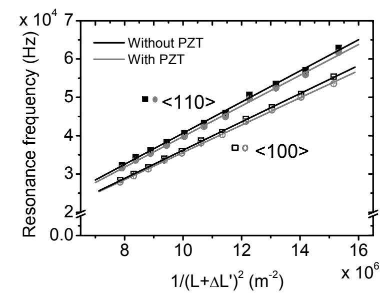

Figure 3. Fundamental resonance frequency versus effective length (L+ΔL') of the cantilevers follows a straight line in both <110> and <100> crystal. orientations of silicon