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## WAFER-SCALE INTEGRATION OF PIEZOELECTRIC ACTUATION CAPABILITIES IN NANOELECTROMECHANICAL SYSTEMS RESONATORS

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For nanoelectromechanical systems (NEMS) to start being a viable alternative to their microscale counterparts (i.e. microelectromechanical systems or MEMS), the fully integrated transduction at the wafer scale represents the ultimate goal to be achieved. By integrated transduction one means both actuation and sensing of movement capabilities of freestanding nanostructures. So far, relevant results in that sense have been obtained at the chip level either by transposing traditional transduction schemes at the nanoscale [1,2] or delivering brand new schemes exclusively adapted to the NEMS realm [3]. Recent efforts to demonstrate full-wafer NEMS with integrated transduction means have been done [4, 5] but remain rather seldom which demonstrates how critical the gap between chip and wafer scale is.

In this work, we demonstrate the integration of piezoelectric actuation means on arrays of nanocantilevers at the wafer scale. We use lead titanate zirconate (PZT) as piezoelectric material mainly because of its excellent actuation properties even when geometrically constrained at extreme scale [6].

The fabrication is performed on SOI 4" P-type (100) wafer (525 $\mu$ m/1 $\mu$ m/340nm). Arrays of four nanocantilevers of different lengths (from 2 $\mu$ m to 10.5 $\mu$ m) have been placed on the wafer so that each array contains same wide devices. The width was varied from 1 $\mu$ m to 2.8 $\mu$ m. A piezoelectric stack including top Ti-Pt (12-120nm thick) and bottom LNO (100nm thick) electrodes as well as the PZT material (150nm thick) has been patterned on each nanocantilever in two covering configurations: full-length or half-length of the nanocantilever. The elastic support beneath the piezoelectric stack is made of the SOI device silicon layer covered by a 30nm thick thermal silicon dioxide (see Figure 1). The main fabrication steps are, in order, silicon RIE definition of the nanocantilevers' shape, lift-off patterning of the piezoelectric stack and sacrificial release of the nanocantilevers, the latter being by far the most

critical step which imposes the final yield (33%) of the implemented fabrication process.. The whole fabrication process is performed at the wafer scale, the lithography steps being realized using a UV stepper photo repeater (I line CANON FPA 3000i4/i5 N.A. 0.63). A photoresist protection layer is provided to cover the wafer and to protect the suspended nanocantilevers prior to dicing into individual chips.

The dynamic characterization of the nanocantilevers is performed in two ways (external and internal actuation-sensing configurations). First, the mechanical integrity of the nanocantilevers is assessed by external piezoelectric actuation and optical sensing of the fundamental mode resonant frequency. Measurements are performed in a home-made fully-automated Fabry-Perot interferometer configuration, under vacuum and ambient temperature conditions. The fully automated option allows convenient characterization at the nanocantilevers level by using the 3D displacement of the chip bearing the nanodevices under the laser spot. The resonant frequency values are compared to theoretical datas issued from finite elements modeling of the nanocantilevers exact configuration, taking into account the specific geometry of the piezoelectric stack (see Figure 2).

The piezoelectric actuation at the nanodevice level is then tested by biasing the top and bottom electrodes as shown in the scheme (see Figure 1). In a first attempt to check the piezoelectric actuation efficiency, no electrical poling of the PZT layer is performed. The results are shown in Figure 3 demonstrating that the piezoelectric layer acts as expected and does not necessarily require electrical poling prior to its use. Nevertheless, in a second attempt, PZT layer is poled at five times the coercitive field value (6.7kV/m) during 15 minutes and the resonant frequency peak shape successively measured shows the enhancement of the actuation efficiency by an increase of the amplitude value of around 30%.

In conclusion, we achieved integration of piezoelectric actuation capabilities on NEMS at the full wafer scale. Further work on the piezoelectric sensing demonstration by collecting the electrical charges generated by the PZT layer using a charge amplifier set-up is currently under progress. This work paves promising ways for NEMS to be used in configurations where transduction capabilities are integrated at the nanodevice level providing fabrication at the wafer-scale.

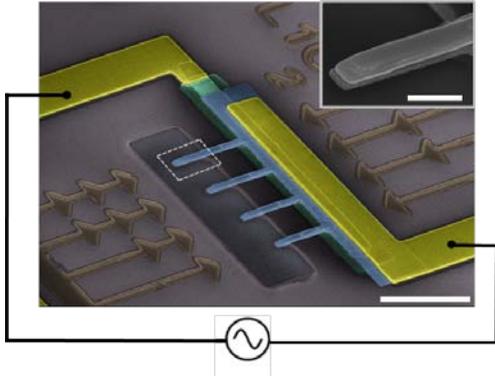


Figure 1: SEM image (false colors) of an array of four nanocantilevers showing the biasing scheme for the internal piezoelectric actuation. The cantilevers dimensions are  $2\mu\text{m}$  wide and respectively  $10.2$ ,  $8.2$ ,  $6.2$  and  $4.2\mu\text{m}$  long (scale bar corresponds to  $20\mu\text{m}$ ). The stack is composed of a  $150\text{nm}$  thick PZT layer (green) sandwiched between a  $100\text{nm}$  thick LNO lower electrode (brown) and a  $12\text{-}120\text{nm}$  thick Ti-Pt upper electrode (blue). A  $30\text{nm}$  thick thermal oxide (purple) grown on top of the silicon ensures the electrical insulation between the stack and the substrate. The structures are actuated by applying an AC voltage between the electrodes through a  $100\text{-}700\text{ nm}$  thick Ti-Au metallization (yellow). The inset is a close view of the  $10.2\mu\text{m}$  long cantilever showing the different layers (scale bar corresponds to  $3\mu\text{m}$ ).

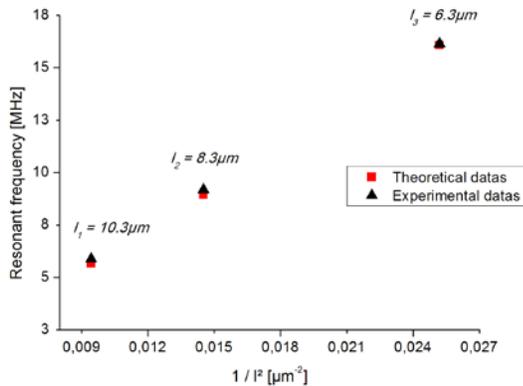


Figure 2: Plot of the fundamental mode resonant frequencies of  $2.4\mu\text{m}$  wide cantilevers with three different lengths  $l$  showing the linear dependence on  $1/l^2$ . Theoretical datas (red) are obtained from finite element modeling. Experimental datas are obtained under external actuation and sensing configuration at

room temperature and under secondary vacuum ( $1,8 \cdot 10^{-6}$  mbars).

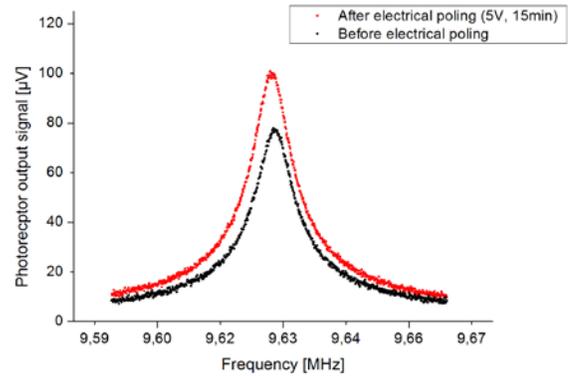


Figure 3: Fundamental mode resonant frequency of a  $2\mu\text{m}$  wide and  $10.2\mu\text{m}$  long cantilever before (black curve) and after (red curve) poling of the PZT thin film. Measurements are achieved according to the integrated actuation ( $12.6\text{mV}$  AC voltage is applied) and external sensing configuration, at room temperature and under secondary vacuum ( $9.8 \cdot 10^{-7}$  mbars). Each datas curve has been averaged 10 times. The structure exhibits a quality factor of 1150 at  $9.63\text{MHz}$ .

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