MATERIAL CHARACTERISATION AT THE MICRO SCALE THROUGH ON-CHIP TESTS

Fabrizio Cacchione[1], Biagio De Masi[2], Alberto Corigliano[1], Marco Ferrera[2]
[1] Department of Structural Engineering. Politecnico di Milano, Milano, Italy
[2] MEMS Business Unit. STMicroelectronics, Cornaredo, (Milano), Italy

ABSTRACT

A series of on-chip test structures where designed, modeled and fabricated for on-chip fracture characterization of 0.7 μm thick polysilicon film. The first test structure is rotational and actuated by comb-fingers capacitors which develop a force sufficient to load the specimens up to rupture; it allow the determination of Young modulus and rupture strength. The second kind of test structure is actuated in the direction orthogonal to the substrate by means of a system of parallel plate actuators, four specimens placed at the four corners of the device are loaded in bending and torsion; they are conceived in order to estimate the value of the shear elastic modulus of the polysilicon film. The third test structure is again actuated by parallel plate capacitors in the direction orthogonal to the substrate and able to load up to rupture a couple of specimens in bending in the plane orthogonal to the substrate; this device has been built in order to measure the resistance of the polysilicon film in these particular loading conditions and to evaluate the possible influence of grain morphology on the mechanical responses. The three different on-chip test structures are briefly described in the paper and the first obtained experimental results are presented and discussed.

1 INTRODUCTION

The mechanical characterization of materials at the scale of micron has become a main issue in the recent scientific literature, due to the fast growing diffusion of Micro Electro-Mecanical Systems (MEMS), (see e.g. Gardner [1], Gad el Hak [2], Lyshevski [3]). Various proposals have appeared which mainly aim at the determination of elastic properties and rupture strength of materials used in MEMS, with special reference to polysilicon (see e.g. Greek et al. [4], Oostenberg and Senturia [5], Sharpe et al. [6], Chasiotis and Knauss [7], Espinosa et al. [8]).

It is the purpose of the present paper to contribute to the issue of mechanical characterization of polysilicon at the scale of micron by describing recent research activities concerning the design and realization of on-chip tests. In Corigliano et al. [9] a fully on-chip procedure for the mechanical characterization of thick polysilicon, based on ad hoc designed MEMS for testing has been proposed. The advantages of on-chip approaches with respect to out of chip ones are first of all related to the possibility to precisely characterise the same material which is used to produce MEMS without any disturbance induced by the manipulation of small specimens in the laboratory. Another advantage consists in the possibility to avoid complicate gripping systems and data acquisition methods. In spite of the above mentioned advantages, a series of disadvantages are still related to the on-chip methodologies, mainly linked to the technological limitations associated to the MEMS production and to the limited possibility to load the specimens in various conditions.

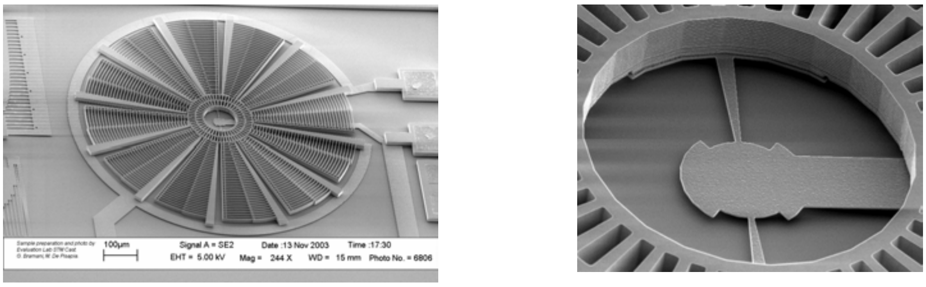
Three test structures are discussed in this paper for the mechanical characterization of 0.7 μm thick polysilicon film. The first one (see also Cacchione et al. [10]) is conceived to load in bending up to rupture, in the plane parallel to the substrate, a pair of doubly clamped specimens. The second, newly designed, test structure allow to have four specimens loaded in out of plane bending and torsion. The third device, also newly designed, allow to load in bending, in the plane orthogonal to the substrate, a couple of doubly clamped specimens.

An outline of the paper is as follows. In Section 2 the rotational test structure for in plane bending tests is briefly described, together with the data reduction procedure and some experimental results. Section 3 is devoted to the description of the out of plane bending and torsional tests, some preliminar experimental results are also presented. The out of plane bending test up to rupture and relevant experimental results are discussed in Section 4. Final remarks are presented in Section 5.

2 IN PLANE BENDING TEST

The in plane bending test is based on a rotational electrostatic actuator, made by 384 comb-fingers capacitors placed on 12 arms, as shown in Fig. 1a. The capacitors develop a force sufficient to load a pair of doubly clamped specimens (see Fig. 1b) up to rupture. The choice of electrostatic actuation was driven by the advantage of great precision and absence of misalignment due to external manipulation.

The specimens have a length of 34 μm and a trapezoidal cross-section (see Fig. 1b). Their width decreases linearly from 5.3 μm to 1.8 μm, this shape was *ad hoc* designed to localize the fracture of the specimen in a specified area through stress concentration. Due to the end constraint of the specimens, the internal stresses were not released. The length of the specimen was kept short enough to avoid Eulerian buckling due to the internal stresses. An estimation of these stresses was done measuring with a profilometer the deformed shape of released cantilevers fabricated on the same die of the test structure. A 3D FE model of the whole structure was used during the design phase.



(a) (b)

Figure 1- (a) Rotational test structure and (b) zoom of the tested specimen.

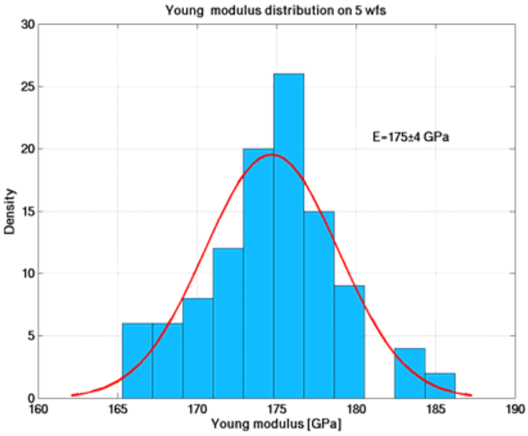


Figure 2 – In plane bending test: experimentally determined Young modulus distribution.

Tests were carried out at room temperature and at atmospheric humidity, with a probe station mounted on an optical microscope. A slowly increasing voltage was applied in order to induce quasi static loading conditions in the specimen. The experimentally determined capacitance vs. voltage plots were transformed in torque vs. rotation plots by making use of analytical relationships between capacitance and rotation and between voltage and electrostatic force.

The measured Young modulus of the tested thin polysilicon film was E = 175 ± 4 GPa; the low dispersion around the mean value confirm the quality and the good reliability of the whole procedure (Fig. 2). Rupture stresses computed after the application of Weibull theory were 1875 ± 333 MPa, with a Weibull modulus m = 6.6.

3 OUT OF PLANE BENDING-TORSIONAL TEST

The second and third (see Section 4) devices for on-chip testing were designed to characterize the out of plane flexural behaviour of polysilicon films and to evaluate the possible influence of grain morphology on the mechanical response. A movement in the direction orthogonal to the substrate was obtained by electrostatic attraction in a newly designed parallel plate actuator. This is based on the movement of a holed plate, shown in Fig. 3a, in the direction orthogonal to the substrate.

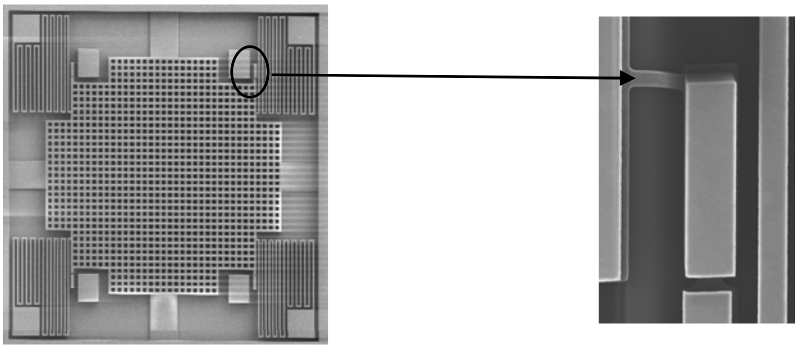

(a) (b)

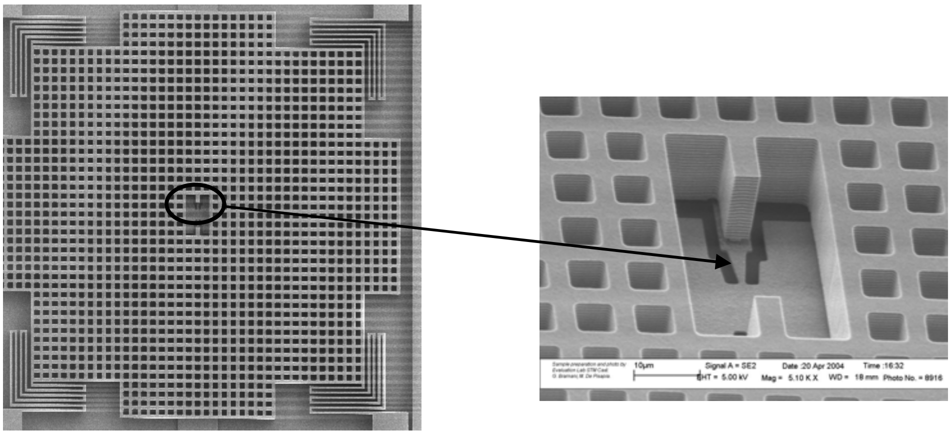
Figure 3 - Electrostatic parallel plate actuator for out of plane bending-torsion test. (a) The whole device; (b) detail of the specimen loaded in bending and torsion.

Four specimens are placed at the four corners of the device, as shown in Fig. 3a, b. When the plate moves in the direction orthogonal to the substrate, each specimen is subject to torsion and bending.

By means of a data reduction procedure similar to the one adopted for the rotational device, with the aid of 3D elastic Finite Element simulations, the elastic shear stiffness which governs the torsional behaviour of the specimens can be measured from the device of Fig. 3, provided that the Young modulus is already known. The results will be published in a forthcoming paper.

4 OUT OF PLANE BENDING TEST UP TO RUPTURE

An actuator similar to that of Fig. 3 was used to obtain specimens loaded in out of plane bending as shown in Fig. 5a, b. A pair of doubly clamped, tapered beam is placed at the centre of the device and loaded in bending in the plane orthogonal to the substrate when the parallel plate capacitor moves.



(a) (b)

Figure 5 – Electrostatic parallel plate actuator for out of plane flexural tests. (a) The whole device; (b) detail of the specimen loaded in bending.

By means of a data reduction procedure similar to the one adopted for the devices described in Sections 2, again with the aid of 3D elastic Finite Element simulations, the rupture strength of the thin polysilicon can be experimentally evaluated. An example of a vertical force vs. vertical displacement diagram is shown in Fig. 6, where it can be appreciated that the global behaviour is practically linear up to rupture. The final results will be published in a forthcoming paper. An example of specimens after rupture is shown in Fig. 7.

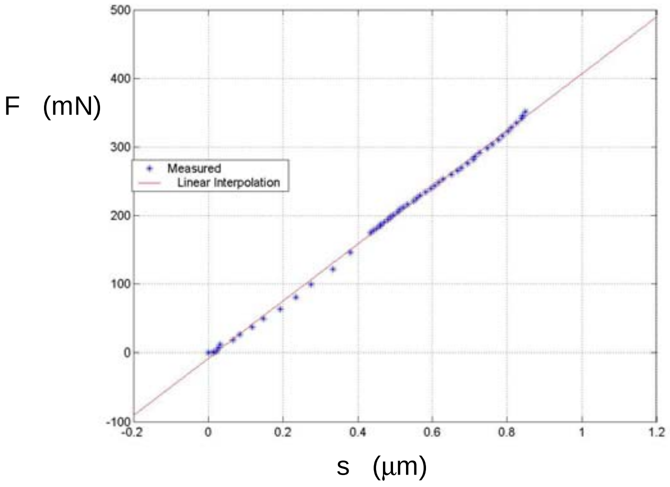


Figure 6 – Electrostatic parallel plate actuator for out of plane flexural tests. Example of vertical force vs. vertical displacement experimental response.

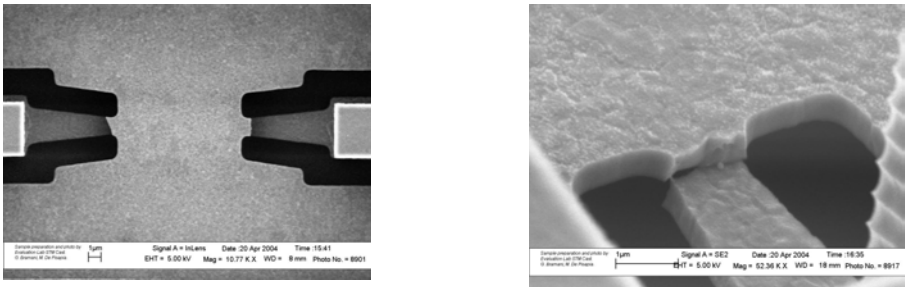


Figure 7 – Out of plane bending test: rupture of specimens.

5 CONCLUSION

Three devices for on-chip mechanical characterization of thin polysilicon film have been briefly described in the present paper. Electrostatic actuation has been adopted in the three cases with comb finger or parallel plate capacitors. The experimental results obtained so far show a good reliability of the whole procedure and a low dispersion of the material parameters. The issue of possible influence on the thin film behaviour of the grain morphology will be discussed in forthcoming works.

Acknowledgement

This research has been carried out in the framework of the EU NoE Patent-DfMM, contract n°507255.

6 REFERENCES

[1] Gardner J.W., Varadan V.K., Awadelkarim O.O., “Microsensors MEMS and Smart Devices”, Wiley, Chichester, (2001).

[2] Gad el Hak M. (editor), “The MEMS handbook”, CRC Press, Boca Raton, (2002).

[3] Lyshevski S.E., “MEMS and NEMS, Systems Devices and Structures”, CRC Press, Boca Raton, (2002).

[4] Greek, S., Ericson, F., Johansson S., Schweitz, J.A., “In situ tensile strength measurement and Weibull analysis of thick film and thin film micromachined polysilicon structures”, Thin Solid Films, 292, 247-254, (1997).

[5] Oostemberg P.M. and Senturia, S.D., “M-Test: a test chip for MEMS material property measurement using electrostatically actuated test structures”, Journal of Microelectromechanical Systems, 6, 107-118, (1997).

[6] Sharpe, W.N., Turner, K.T., Edwards, R.L., “Tensile testing of polysilicon”, J. of Experimental Mechanics, 39, 162-170, (1999).

[7] Chasiotis I., Knauss, W.G., “A New Microtensile Tester for the Study of MEMS Materials with the aid of Atomic Force Microscopy”, Experimental Mechanics, 42(1), 51-57, (2002).

[8] Espinosa H.D., Prorok B.C., Fischer M., “A methodology for determining mechanical properties of freestanding thin films and MEMS materials”, J. Mech. Phys. Solids, 51, 47-67, (2003).

[9] Corigliano A., De Masi B, Frangi A., Comi C., Villa A., Marchi M., “Mechanical characterization of polysilicon through on chip tensile tests”, J. of Microelectromechanical Systems, 13, 200-219, (2004).

[10] Cacchione F., De Masi B., Corigliano A., Ferrera M., Rupture tests on polysilicon films through on-chip electrostatic actuation”, Proc. Eurosime2004, Brussels, May (2004).