Subproject C2: "A Novel High Aspect Ratio Technology for MEMS Fabrication Using Standard Silicon Wafers"

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INTRODUCTION

A novel high aspect ratio technology for the fabrication of Air gap Insulated Microstructures has been developed within the Collaborative Research Project 379 and was presented recently [1]. This three mask level technology is based on a throughout dry fabrication process using standard silicon wafers for the fabrication of high aspect ratio structures. The released single crystal silicon structures are free of any additional coating after processing and fixed by interconnection beams to the bulk material. In contrast to other solutions [2] only one release etch step is necessary. As a result of the novel process flow the silicon structures are surrounded by air gaps. Thus a strongly reduced parasitic capacitance with respect to bulk silicon is achieved. These AIM structures were fabricated and tested with respect to mechanical stability, temperature dependence and electrical behavior of an exemplary oscillator structure. Fig.1 is a principle drawing of an AIM structure with a seismic mass fixed by an anchor. Other solutions are using high aspect ratio structures too – usually in combination with special release/isolation processes (SCREAM [2], LISA [3]) or on the base of SOI wafers [4]).

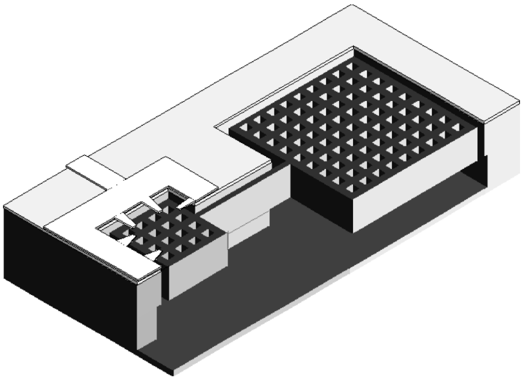

Figure 1: Principle drawing of an AIM structure

STRUCTURE AND PROPERTIES OF THE INTERCONNECTION BEAM

The interconnection beams have to ensure the mechanical and electrical contact between the seismic mass and the bulk material represented by the conducting layer. Therefore, the properties of the beams have to be considered for both tasks. Mechanical loading of the structures by various methods identifies the interconnection beam as the weakest point in the mechanical system. An improvement of the stability and reliability of the interconnection beams will be most effectively for an increase of the reliability of the whole microstructure.
The mechanical stability and reliability of an AIM can be increased through an increasing number of interconnection beams. Four structures (Fig. 2), with 34, 50, 66 or 82 interconnection beams, consisting of aluminium and spacer oxide, are tested by applying a force on top of the structures.

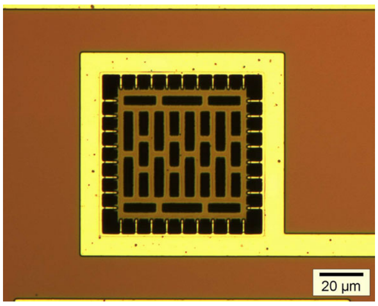

Figure 2: Top view (photograph) of a test structure using 34 interconnection beams

The resulting deflection depending on the force has been measured. As expected the increasing number of beams multiplies the maximum load of the structure. On the other hand a higher number of beams results in a higher area consumption of the structure, too. Thus material (table 1) and geometry considerations as well have been carried out in order to ensure a high fatigue limit and a high reliability of the mechanical components. The mechanical properties of free standing aluminum or aluminum alloy beams is described elsewhere [5].

Table 1: Parameters and results of the investigated material stacks deposited on 4“ standard silicon wafers

Wafer number	**Thermal SiO_2 layer**		**PE-SiN layer**		**Al layer**	**Material stack**	**Material stack after 400°C annealing**
	Thickness [nm]	Stress [MPa]	Thickness [nm]	Stress [MPa]	Thickness [nm]	Stress [MPa]	Stress [MPa]
1	517,5	-351,6	0	0	300	-206,3	-103
2	514,5	-324,1	0	0	300	-179,7	-70
3	290,6	-381,8	250	350,5	300	-16,5	95
4	305,0	-396,3	250	319,4	300	-32	95
5	104,5	-382,2	465	111,2	300	22,5	140
6	107,5	-389,8	465	76,3	300	1,3	122

Various properties have to be ensured by the fabrication of the beams. Tensile stress of the deposited material or material stack used for the beams is required. The stress acts as a force on the released structure. For compressive stress an unsteady mechanical system could be obtained and tilting of the seismic mass becomes possible. Another important characteristic of the beams is the electrical conductivity. The basic AIM technology uses aluminum as beam material deposited by a physical vapor deposition (PVD) step on silicon because of the good conductivity and the tensile stress of the material. The mechanical properties of beams consisting of pure aluminum were characterized by measuring the deflection of a test structure as explained earlier. It illustrates the typical behavior of an elastic material with a linear and a nonlinear part before fracturing is observed. The same test is used for the characterization of beams consisting of aluminum and spacer oxide (plasma enhanced deposited silicon dioxide; Fig. 3 and 4). The spacer oxide at the sidewall of the interconnection beams is a residue of the material used as hard mask material for anisotropic deep silicon etching. The mechanical properties of the aluminum-oxide sample depend mainly on the properties of the silicon dioxide. The deflection of the beams is linear until the cracking point is reached. This is a typical behavior of a brittle material like silicon dioxide and is different to the behavior of a plastic deformable material like aluminum.

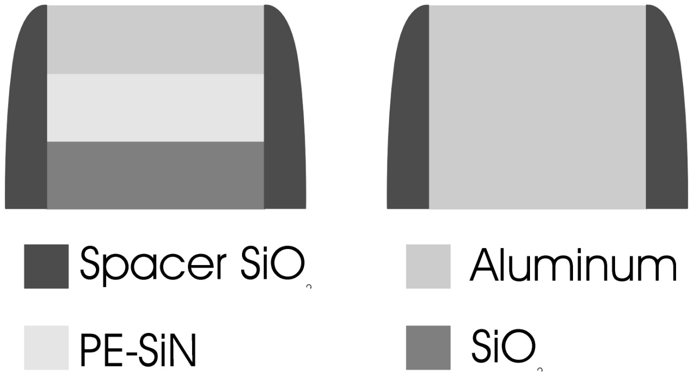

Figure 10: Choice of the investigated material layer stacks

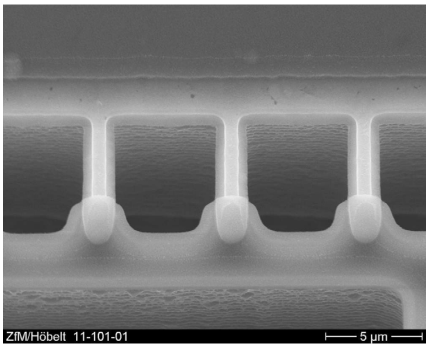

Figure 11: Top view of interconnection beams consisting of aluminum and spacer oxide

A first result of this measurement is that the maximum load per beam can be increased by using a stack of materials for the beams instead of pure aluminum. Using a material stack would also increase the shock resistance and lower the fatigue by minimizing the deflection (stress) inside the beam which results in a higher reliability of the whole AIM. The improved beams should consist of a material stack based on Al, PE-SiN and SiO2. Al is mainly used as a conducting material for the electrical contact between the seismic mass and the conductive layer. The mechanical properties of the beams are primarily defined by the PE-SiN and SiO_2 layers respectively. The high Young’s modulus of silicon nitride (290 GPa) [6] minimizes the resulting deflections of the whole beam. The adjustability of the tensile stress by varying the deposition parameters is an important feature of the material. The SiO_2 layer ensures a high electrical isolation between the conductive layer and the bulk silicon and also passivates the bottom side of the PE-SiN layer during plasma etch processes. The sidewalls of the beams are also protected by SiO_2 films deposited later.

The resulting tensile stress of the material stack depends on the materials and process parameters. Six 4” wafers with three different combinations of material stacks and process parameters were prepared. The tensile stress was concluded from measurements by the FLX-2900 (Tencor). The tensile stress of a deposited layer is calculated by measuring the deformation of the wafer using a laser and the layer thickness. During the CMOS-compatible annealing process (nitrogen environment, 400 °C) the resulting stress of the material stack increases. This effect is based on the typical behaviour of a thin metal layer deposited by PVD [7] and based on a growth of the grain size inside the layer. This growth of the grain size is responsible for an increase of the density inside the metal layer and therefore for a decrease of the layer volume because of the constant number of molecules. The decrease of the layer volume results in an increase of the tensile stress, which affects the whole material stack. No changes should occur inside the SiO_2 and SiN layer because of the higher deposition temperature of the materials. The long-term behavior shows that the tensile stress of the material stack changes only within the first two weeks. After this period of time no changes could be found. It is possible to create a layer stack of SiO_2, PE-SiN and Al defining the resulting tensile stress of this system by changing the parameters for the deposition of the PE-SiN and an additional annealing step. As a result the tensile stress is temperature and long-term stable. Therefore this kind of layer stack can be successfully used for the interconnection beams.

ACKNOWLEDGEMENT

The authors would like to thank the staff of the Center of Microtechnologies for assistance in processing the samples and devices, especially T. Werner, R. Schuberth and B. Brämer. This work was funded by the German Research Foundation (DFG) within the Collaborative Research Centre SFB 379 „Micromechanical Sensor– and Actuator–Arrays“.

REFERENCES

[1] A. Bertz, M. Küchler, R. Knöfler, T. Gessner, A novel high aspect ratio technology for MEMS fabrication using standard silicon wafers, *Sensors and Actuators A 97-98 (2002) 691-701.*

[2] Z.L. Zhang, N.C. MacDonald, An RIE process for submicron silicon electromechanical structures, *J. Micromech. Microeng.*, 2 (1992) 31-38.

[3] U. Sridhar et al., Single crystal silicon microstructures using trench isolation, *Tech. Digest, Transducers ’99, Sendai, Japan, 7-10 June, 1999, pp 258-261.*

[4] M.A. Lemkin, T.N. Juneau, W. A. Clark, T.A. Roessig, T.J. Brosnihan, A low-noise digital accelerometer using integrated SOI-MEMS technology, *Tech. Digest, Transducers ’99, Sendai, Japan, 7-10 June, 1999, pp.1294-1297.*

[5] H.-J. Lee, G. Cornella, J. C. Bravman, Stress relaxation of free-standing aluminum beams for micromechanical systems applications, *Applied Physics Letters, 76 (2000), 3415-3417*

[6] G. Gerlach, W. Dötzel, *Grundlagen der Mikrosystemtechnik*, Hanser, München 1997

[7] V. Weihnacht, *Besonderheiten der mechanischen Eigenschaften und der Mikrostruktur dünner, polykristalliner Kupferschichten*, Dissertation, Technische Universität Bergakademie Freiberg, 2001

[8] A. A. Ayón, C. C. Lin, R. A. Braff, R. Bayt, H. H. Sawin, M. A. Schmidt, Characterization of a time multiplexed inductively coupled plasma etcher, *J. Electrochem. Soc. 146 (1999) pp. 339*

[9] Roman Knöfler, Klaus Wolf, Enrico Ahl, Ulf Kotarsky, Wolfgang Manthey, Matthias Küchler, Andreas Bertz, Thomas Gessner, Micromechanical Scanning Device for Large Vertical Range with High Resolution, *Proceedings of the 7th International Conference on New Actuators, Bremen, Germany, 2000, pp. 83 - 86*