Flexible and conformable strain gauges for smart pressure sensors systems: static and dynamic characterization.

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***Abstract*— An innovative segment of the semiconductor and electronics industry in the last years is driven by new sensors embedded in smart devices and systems with thin, connected to existing infrastructures via standard communication interfaces. The increased maturity of industrial sensor technologies and associated readout electronics enabled new products penetrating multiple market sectors. Among the different classes of smart sensing systems that can be realized with thin and truly flexible form factor, thin film strain gauges are ideally suited for the implementation of pressure sensing membranes. In this work we will focus on the development of static and dynamic testing methods of a strain gauge module whose applications are intended as a flexible and conformable strain/pressure sensor, adaptable for wireless communications.**

***Keywords*— Flexible; Sensors; Strain-Gauge; Device; Nanosensors**

I. INTRODUCTION

Innovation along the path of smart systems and smart devices is characterized by the introduction of disruptive technologies and applications that enable entirely new products which do not exist or it is not possible to develop with conventional semiconductor technologies, by e.g. the System-On-Chip approach. Several examples of “Electronics on flexible foils” have been demonstrated recently [1-5], as enabling technology for smart disposable systems integration. It is expected that some of the new concepts could represent the next disruptive innovation technology in the decade, after MEMS, OLED Displays, Smartphones and Smart Power integration, since it allows to fully achieving innovative system solutions on substrates other than silicon that can be flexible, conformable, lightweight, transparent and cost-effective. Integrating an antenna for inductive coupling in the same foil substrate as the disposable sensor and electronics will allow for both energy and data transfer [6-8], to both operate as well as to test and calibrate the whole system from a standard RF transceiver infrastructure (Fig.1). Of the several smart sensor systems that can be realized, strain gauge sensors based on resistors can be usefully exploited as flexible and conformable strain/pressure sensors [9-12]. In this work we will focus, in particular, on the development of static and dynamic testing methods of a strain gauge module whose applications are intended as a flexible and conformable strain/pressure sensor, adaptable for wireless communications.

In this respect, we have designed and developed a strain gauge module totally integrated on a polyimide (PI) plastic foil consisting of a set of four metal bespoke resistors integrated with an antenna intended for energy and wireless data transfer.

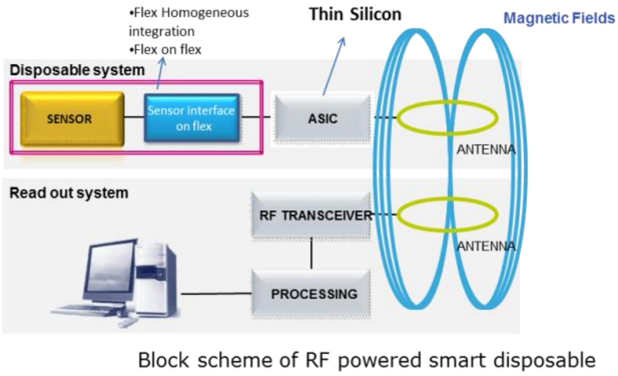

Fig.1. Integrated Smart system sensors concept

II. EXPERIMENTAL

A. *General*

Developed process steps allow to provide conductive tracks, electrodes antenna and sensor functionalities all in the same substrate, which is a 3 micron thick plastic layer, made by polyimmide, deposited by spin coating on top of a rigid silicon wafer carrier with a sacrificial thin metal layer in between the silicon and the plastic substrate.

This approach has been proven to successfully enable manufacturing of ultra-thin and truly flexible electronic multifunctional systems by means of conventional semiconductor fabrication process, and eventually add organic and inorganic semiconductor, conductors and dielectric materials. In the case of wireless strain gauge, only metallic layer materials and electrodes have been deposited and patterned by means of standard photolithography on a 6” foil substrate on wafer carrier (see Fig. 2).

Fig. 2. Strain gauges modules developed on PI foils equiped with an integrated antenna for wireless comunications and energy transfer.

In order to design the thin film metallic strain gauge patterns, mechanical and electrical simulations of radial and tangential strains in the substrate membrane allowed us to define both the optimal positioning and shape of the winding resistors and to control their values. Another set of simulations in the RF domain have been performed in order to integrate the antenna for radiofrequency (RF) communication.

The set of four strain gauge resistors have been characterized after manufacturing in two ways. First with the substrate yet on the 6” wafer carrier, in order to determine the statistical dispersion of their resistance values (Fig. 3), and then on individual devices, in order to characterize their sensitivity as strain gauge sensors (Fig. 4-7).

An average value of 3.8 kΩ for the resistance has been obtained from statistical analysis on wafer, with a dispersion of values ranging from 3.5 kΩ to 4.1 kΩ as reported in Fig. 3.

A. Strain gauge sensor measurement Setup

In order to characterize the sensor strain gauge under pressure, a bespoke measurement system and setup was developed. Such a system allowed us to follow the four sensors performance both for static and dynamic measurements.

In particular, a pressure signal is generated by means of a syringe pump. The pressure, after a T-branch in the connecting tubes, is monitored by a reference pressure sensor of the Honeywell 40PC series which is biased and read by means of a data acquisition system DAQ (Fig. 4a). Simultaneously, the same generated pressure signal is applied to a hermetically sealed chamber housing the strain gauge sensor system (Fig. 5). To complete the measurement setup on the strain gauge sensor system, a multimeter, connected to a PC with a GPIB port, reads the resistance of each single resistor (Fig. 4a). All instruments are controlled via a LabVIEW™ interface.

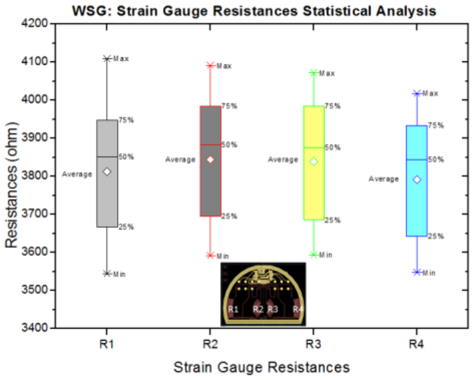

Fig.3. Measurement of strain resistances made on wafer (before peeling off the substrate from the wafer carrier).

Electrical connections of the sensor system with the measurement setup was made by using standard probe tips acting on the sensor pads (Fig. 4b), while a constant pressure value was applied (static measurement setup). Afterward, a wire bonding was made by using 2 mils Au wires, which allowed to perform dynamic electrical testing under pressure variations (Fig. 4b).

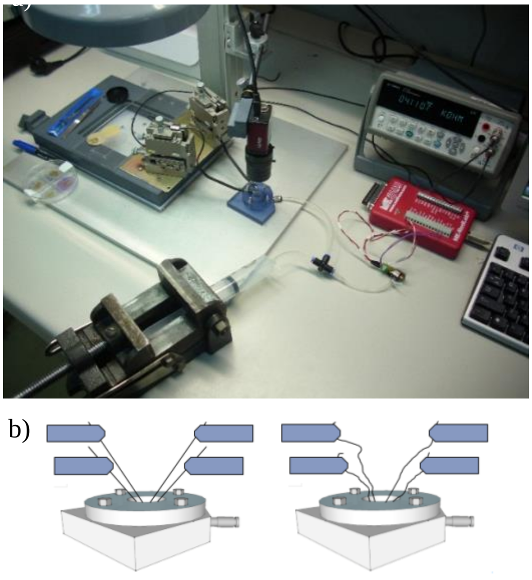

Fig.4. a) View of the measurement setup exploited to follow the SSG pressure measurements; b) Two configurations exploited to contact the strain gauge sensor system pads: on the left with needles connected to probes; on the right with pads bonded wires connected to probes.

In order to characterize the device as pressure sensor system a single device was prepared. First it was laminated on a thicker membrane substrate whose mechanical properties have the same characteristics of the final application package substrate. In our experiment the device was glues by an epoxy-based adhesive to a stiff polycarbonate substrate (1mm thick). The sample was then cut in a circular shape and locked in the chamber of the retention system to close hermetically the pressure chamber (Fig. 5a and 5b). Air leakage is verified by monitoring that the applied pressure was constant during a sufficient time period.

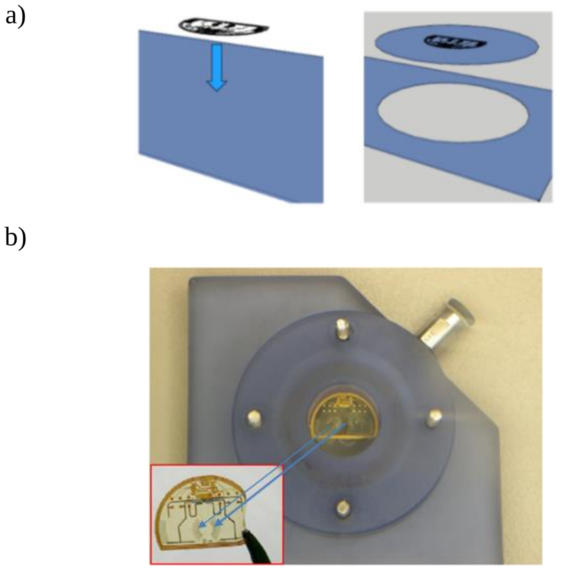

Fig.5a. Sketch of a strain gauge system device stacked on a polycarbonate substrate and fixed on (b) a hermetically sealed chamber system.

III. RESULTS

The dependence on the applied pressure signals of the resistance of those strain gauge devices indicated by arrows in Fig. 5b, has been measured quasi-statically and after that by implementing dynamic procedures also. A first check of the static response of the strain sensor was done by placing two probe tips on the pair of terminal pads of the resistor under measurements (see Fig.4b). Examples of such kind of measurements are reported on panel a) and b) respectively of Fig.6. In each panel the sampling of the resistance is reported as a function of time when a value of pressure is applied. Each color in the graphs distinguishes a value of the applied pressure. The values reported on panel a) refer to a quasi-static measurement of the resistance obtained by sweeping the pressure signal from 1.0 atm to 3.2 atm. Whereas, panel b) reports the sampling of the resistance obtained by sweeping the pressure from 3.2 atm back to 1.0 atm. According to these measurements, it resulted that after a quasi-static sweep of the pressure going from higher pressure to lower pressure, the variations of the resistance are not the same of those values obtained by sweeping from lower to higher pressure. This effect is due to a residual membrane strain determined by the sliding of the membrane under the fixing system at higher pressure. By plotting the resistance values sampled from the quasi-static measurements as a function of the applied pressure for several pressure sweeps as described in panel a) of Fig.6, we obtained a linear trend of the measured resistance as a function of the applied pressure (Fig. 7).

In order to overcome the mismatch obtained from the resistance measurements obtained with the probe tip contact method and in order to reduce the impact of probes inertia during quasi-static measurements, wire bonding of the resistors pads by means of thin metal wires was adopted, as shown in Fig 4b.

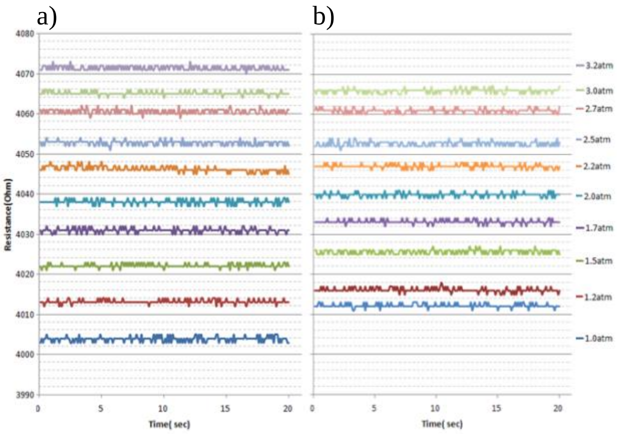

Fig. 6.a) Quasi-static measurements sampling the resistance values for a central resistor in the device glued on polycarbonate foil and fixed to an airtight system, obtained by sweeping the applied pressure from 1.0 atm to 3.2 atm. b) Measurements sampling the same resistance by sweeping the applied pressure from 3.2 atm to 1.0 atm. A mismatch between the two cases has been observed.

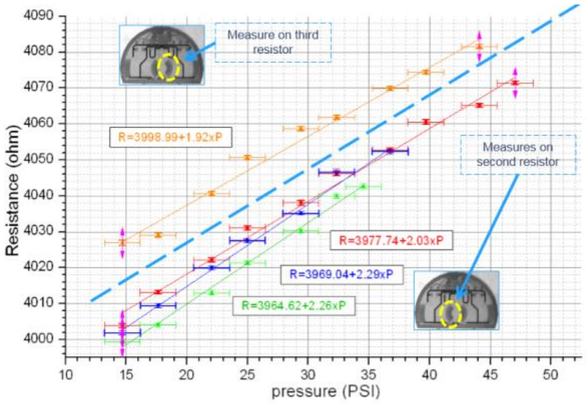

Fig. 7. Sensitivity measurements upon several pressure sweeps, reported for the two central strain gauge resistors only. Measurement data spread and linear fit are reported, and actually consistent with the intercept values of the resistances R_0 and the strain gauge sensitivity. The dashed line demarks a separation of the measurement done on the central right resistor from three measurements done on the central left one.

More measurements were done in order to characterize the dynamic response of the strain gauge sensor system to faster variations of the applied pressure signals. Typical sample data of the pressure dynamics and the resulting resistance value over time is reported in Fig. 8, for one of the strain gauge sensors in the device. Based on the full set of collected data, it has been possible to characterize the linearity of resistance variations vs. applied pressure and to check it on three different devices. The results, as shown in Fig 9, outline fair consistency of data among the three different strain gauge sensors, measured through wire bonding, with an average slope sensitivity of 1.8Ω/PSI, which is consistent as well with the values obtained by probe tip measurements.

Going into the details, the values of R_0 (intercept on the R-axis) align well with measures of the same resistors when the system was bonded on the wafer carrier (Fig. 3): this means that the peel-off and subsequent bonding on the target substrate does not introduce any relevant residual stress.

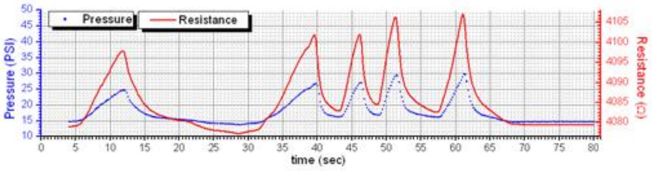

Fig. 8: Data sampling of the applied pressure and the resulting resistance for a given strain gauge sensor device.

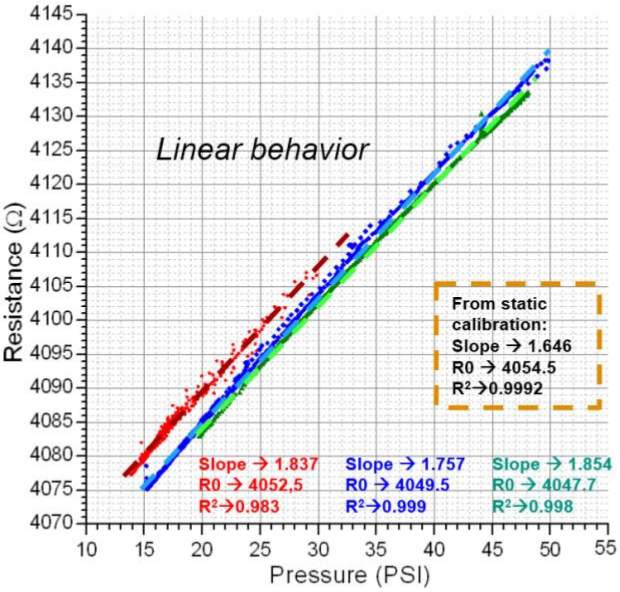

Fig. 9. Resistance vs. applied pressure plot with a linear fit of experimental data for several wire bonded resistors. The pressure is varied dynamically both from high to low and vice versa. Data refer to three different samples of strain gauge sensor systems distinguished by different colors. Their slopes and intercepts R_0 are consistent to each other.

Using an average value of the slope-sensitivity and intercepts resistance R_0, we finally obtained the calibration curve. By this method, in fact, direct reading of the pressure acting on the membrane by means of a reference sensor and by measuring the resistance variation of each strain gauge sensor allowed to extract the calibration parameters used to obtain the sensor measurement characteristics as shown in Fig. 10. A good agreement between data read by the reference pressure sensor and by the new strain gauge sensor system is reported.

IV. CONCLUSIONS

In conclusion, we have modelled, designed and manufactured metal strain gauge resistors on ultra-thin PI substrates obtained by standard lithographic process which can be adapted conformably to any target substrate and used as resistive pressure sensor flexible membranes. We have implemented both quasi-statically and dynamic procedures to fully characterize and calibrate the sensor system in response to different pressure signals. The results obtained show that strain gauge sensor systems are suitable to work as pressure sensor with good sensitivity, fast response to pressure stimuli acting on the membrane substrate, with good reproducibility.

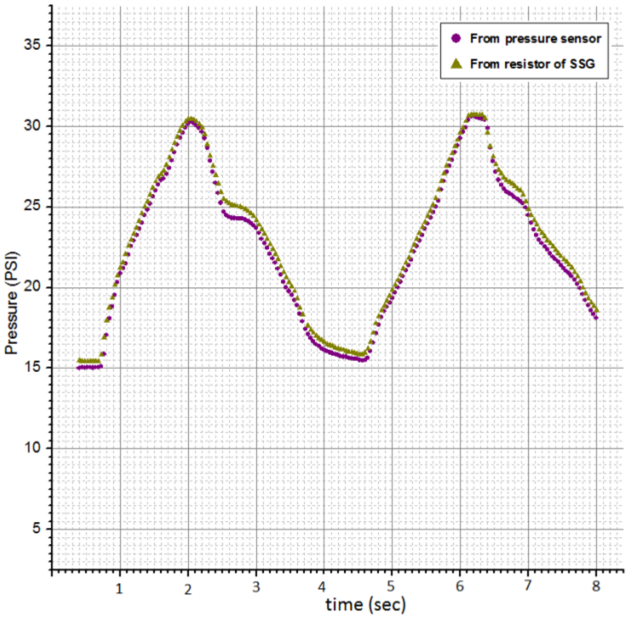

Fig. 10. Comparison between the pressure sampling read by the reference sensor (circle) and by one of the four strain gauge resistors of the device under test (triangle), after calibration.

The strain gauge sensor system is ideally suited for exploiting more electronic functionalities that are needed in order to develop an autonomous smart sensor system. A combination and integration in the same substrate of an unpackaged thinned silicon die is adopted in the whole system design in order to implement the following functions:

1) Analog sensor Front-End (AFE). This block will connect and provide voltage stimuli to the 4 thin film strain gauge resistors in the same substrate according to a conventional Whetstone bridge configuration. This way the sensitivity of the single sensor units will be combined and maximized to perform as a pressure sensor device on the basis of the deformation of the membrane substrate;

2) Radio-Frequency Front-End (RF-FE). This is intended to connect the device with the loop antenna manufactured in the

same substrate, which allows the device to both harvest energy via an inductive coupling with an external reader (e.g. a smartphone equipped with a NFC standard reader device) and to modulate the electromagnetic field so that the information acquired from the sensor is transmitted wireless to the external reader device.

3) Other functions such as Analog to Digital Conversion, Non-volatile memory to store and retrieve individual sensor calibration data, High speed data processing, Communication standard protocols (e.g. ISO 15693 – 18092 NFC).

All the above functionalities need to be embedded in the same substrate with the strain gauge sensors, interconnects and antenna, and need to guarantee the same form factor and mechanical behavior as the target substrate, in order not to influence the membrane capability of acting as pressure sensor.

Today these functionalities are readily available from the silicon industry and actually adopted in multiple application sectors (e.g. NFC tags, autonomous temperature sensors, etc.) in form of small tiny ICs.

The actual challenge is therefore to make these IC devices fully compatible and easy to be handled and assembled on a ultra-thin, flexible and low cost plastic substrate, which might be less robust and temperature-resistant than conventional Printed Circuit Board substrates, where standard IC devices are generally assembled.

Current semiconductor manufacturing capabilities of silicon ICs provide standard approaches to manufacture those electronic IC devices in 8" (or higher diameter) wafer substrates that can be thinned down to about 100 μm, with well-established back-grinding processes, which is still not enough to secure the compliance to the desired form factor of flexible electronic substrates as mentioned above. However the most recent technologies allow for obtaining ultra-thinned dice down to e.g. 25 μm that can be assembled with various methods (e.g. flip-chip or by printed bonded wires) directly on the surface of the flexible substrate where other functionalities (the strain gauge sensor system and antenna) are developed.

Flexible and conformable ultra-thin silicon dice of integrated circuits can be also stacked and integrated "foil" to "foil" on flexible, conformable and stretchable polymer substrates. Steps going towards the engineering of the thinning processes of integrated circuits are investigated, by considering for example silicon ICs manufactured on SOI (silicon on insulator) wafers and etched down to few micron thick layers [13]. Other concepts for smart sensor systems hybrid integrated on flexible substrates can also be exploited and applied to multiple market sectors, including e.g. e-skin for robotics, wearable or implantable medical devices, smart connected objects (IoT), and many others.

ACKNOWLEDGMENTS

This work has been funded by MIUR by means of the national Program PON R&C 2007-2013, project "Elettronica su Plastica per Sistemi Smart disposable" (PON02 00355 3416798).

REFERENCES

[1] H. Klauk (Editor), Organic Electronics: Materials, Manufacturing, and Applications, Wiley, 2006, ISBN: 978-3-527-31264-1; H. Klauk (Editor), Organic Electronics II: More Materials and Applications, Wiley, 2012, ISBN: 978-3-527-32647-1

[2] E. Cantatore (Editor), Applications of Organic and Printed Electronics: A Technology-Enabled Revolution, Springer-Verlag; 2013 ISBN: 978-1-4614-3159-6.

[3] L. Fortuna, M. Frasca, M. Goffrè, M. Rosa, N. Malagnino, A. Marcellino, D. Nicolosi, L. G. Occhipinti, F. Porro, G. Sicurella, E. Umana, and R. Vecchione, "On the Way to Plastic Computation", in IEEE Circuits and Systems Magazine, 8 (3), art. no. 4609960, 2008 pp. 6-18.

[4] L. G. Occhipinti, M. La Rosa, N. Malagnino, A. Marcellino, D. Nicolosi, F. Porro, G. Sicurella, R. Vecchione, V. Vinciguerra and M. V. Volpe, "Printed Organic Electronic Technology Platform Enabling the Design and Manufacturing of Integrated Circuits Towards Plastic Microprocessors" in Micro and Nanosystems vol. 2 issue 1, 2010 ISSN: 1876-402, pp. 1-14 (14).

[5] V. Vinciguerra, M. La Rosa, D. Nicolosi, G. Sicurella, and L. G. Occhipinti, " Modeling the gate bias dependence of contact resistance in staggered polycrystalline organic thin film transistors", in Organic Electronics, vol. 10, Issue 6, Elsevier 2009, pp. 1074-1081.

[6] T. Hongell, I. Kivela, I. Hakala, "Wireless strain gauge network — Best-hall measurement case", 2014 IEEE Ninth International Conference on Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP), 2014, pp. 1-6, DOI: 10.1109/ISSNIP.2014.6827665

[7] S. Arms, C. P. Townsend, "Wireless Strain Measurement Systems - Applications & Solutions," in NSF-ESF Joint Conference on Structural Health Monitoring, pp. 3-5. Strasbourg, France October 2003

[8] Y. Chen, J. Chiang, H. Chu, P. Huang, A. Tsui, "Sensor-Assisted WIFI Indoor Location System for Adapting to Environmental Dynamics," in Proceedings of the 8th ACM Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems, pp. 10-13. Montreal, Quebec, Canada October 2005

[9] J. G. da Silva, A. A. de Carvalho, and D. D. da Silva, "A strain gauge tactile sensor for finger-mounted applications" IEEE T. Instrumentation and Measurement 51(1) 2002 pp. 18-22.

[10] Yihao Zhu; Koley, G.Southeastcon, "Highly sensitive pressure sensor using Au patterned polydimethylsiloxane membrane for biosensing applications: Correlation of sensitivity and effective sensing range with membrane thickness" 2013 pp. 1-6 Proceedings of IEEE, DOI: 10.1109/SECON.2013.6567396 IEEE Conference Publications

[11] A. Bonvilain; M. Gangneron, "First experimentations of microsensors microfabricated on a long and thin medical needle", Design, Test, Integration and Packaging of MEMS/MOEMS (DTIP) Symposium, 2014 Pages: 1 - 4, DOI: 10.1109/DTIP.2014.7056636.

[12] Qi Wang; Zhigang Feng; Shida, K. "A self-validating pressure sensor Sensors", 2008 IEEE Year: 2008 pp.1032-1035, DOI: 10.1109/ICSENS.2008.4716619

[13] R.S. Dahiya, A. Adami, C. Collini, and L. Lorenzelli, "Fabrication of single crystal silicon micro-/nanostructures and transferring them to flexible substrates", Microelectronic Engineering, 98, 2012 pp. 502-507. (doi:10.1016/j.mee.2012.07.084)