Overview of the technologies used in the fabrication of MEMS/NEMS actuators for space applications

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DOI: 10.13111/2066-8201.2023.15.3.5

Received: 10 April 2023/ Accepted: 30 May 2023/ Published: September 2023

Abstract: *Given the advantages in terms of weight, size and cost and because it can withstand severe shocks and temperature changes, the MEMS/NEMS sensors are widely used in the aerospace domain. This paper presents a brief history of the scientists who made reference to micro and nano technologies for the first time, followed by a synthesis of the leading technologies used in the manufacture of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) intensively used in aerospace industry. After reviewing the latest technologies used in the manufacture of MEMS/NEMS sensors, the paper continues with predicting the current state regarding the development of NEMS and MEMS, respectively.*

Key Words: *nanoparticles, microtechnology, multilayer structures, microelectronic systems, nanoelectromechanical systems, gyroscopes*

1. INTRODUCTION

On 29 December 1959, Nobel Prize winner Richard Feynman, in his speech "There is Plenty of Room at the Bottom" at the annual meeting of the American society of Physics, made his first allusion to nanotechnology, referring to the still new advantages of miniaturization. In his speech, he described a discipline aimed at manipulating smaller and smaller material units, allowing atoms to be arranged at researchers' will [1].

This vision of the physicist is seen by many as the first scientific discussion about nanotechnology. However, it was only in 1974 that the University of Norio Taniguchi from Tokio adopted nanotechnology. Taniguchi has delineated engineering at the micrometer scale - so-called microtechnology - and introduced a new engineering, this time at the level below the micrometer, which he called it nanotechnology [2].

The physicist Eric Drexler classified nanotechnology products into three main categories: assemblers, reproductions, and nanocomputers.

Assemblers are technologies designed to produce new materials with the necessary microstructures, ensuring that each atom or molecule is positioned in the right place, reproductions are technologies that produce, in a continuous stream, the finished products that humanity needs, including machines that are faithful copies of themselves and the nanocomputers are electronic computing machines with the power of future generations' supercomputers but with nanometric dimensions.

Accurate nano architectures ranging from 10 to 100 nm have been successfully synthesized. Components of this type involve a dendrimer's reactive skin with a reactive core of a dendrimer. Thus, the new components refer to dendrimers' molecular compositions, leading to a subsequent research stage to the production of new phases using copolymers. The research into and obtaining new copolymers of the following components: nanocrystal, nanoparticles, and structures in nanoparticles are recent (Fig. 1).

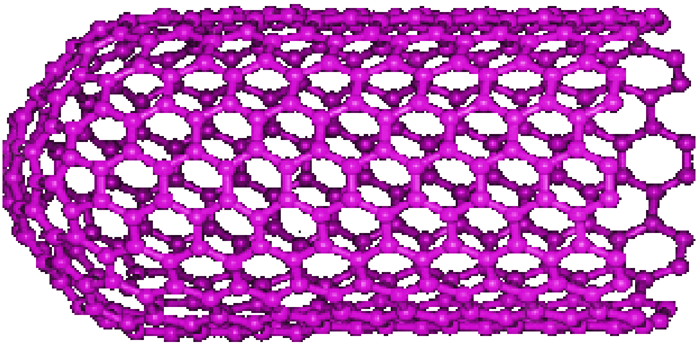

Fig. 1: The Carbon nanotube molecule [1]

Significant progress has been made in obtaining nanocrystal in recent years. In particular, many common materials such as metals, semiconductors, and magnets can be made from nanocrystal based on colloidal chemical processes.

The liaison exchange concept has been well developed, allowing nanocrystals characterized by a limited distribution of the diameter (generally with a diameter variation of between 5-15%) to be isolated and subsequently used as chemical reagents. In this area, a key factor was research into the role of dimensions based on fundamental studies in physical chemistry and condensed matter physics [1].

The exciting discovery of fullerenes was followed almost immediately by the discovery of carbon nanotubes. The extraordinary construction of nanotubes has proven promising in producing matrices for new materials. Due to topology and small interatomic ties, there are no surface defects in carbon nanotubes [1].

As a result, individual nanotubes are characterized by ideal electrical, optical, and mechanical properties.

Regarding structures in nanoparticles, it should be noted that controlled particle production is an effective synthetic method necessary to develop nano-sized structures and is the technology for manufacturing various products, from ceramic components to aerospace domain.

Nanostructures can be found in various forms, the most important of which are: agglomerations of nanoparticles and air vents.

It should be noted that, in particular, these structures are characterized by their morphology (for example, their size of fractures and number of coordination) and binding energy, which keeps particles together.

The possibilities for using nanomaterials according to their chemical properties were presented in Table 1. In terms of the emergence and development of the engineering microtechnology that underpins the development of the MEMS (microelectromechanical systems), we can consider the XVth century as a starting point with the first pocket watches. The acronym for electromechanical microsystems (MEMS) was officially adopted by a group of participants at the 1989 Micro-operated Robotics Workshop scientific conference in Salt Lake City, USA. Here, the term MEMS was used to describe the manufactured resonant structures used in frequency stabilizers briefly.

At the same time, European researchers used the term micro-stem technology to describe the same concept, this technology used to manufacture a micro-system.

The first to be interested in this technology in the early 1990s was DARPA (Defense Advanced Research Projects Agency) and the U.S. Air force, which started to finance such projects. The idea of MEMS manufacturing has been so fast in industrialized countries that only three years after the MEMS's birth, there were over 300 companies and research institutes involved in their development.

Today, Plunkett Research Ltd. estimates that more than 2.200 entities worldwide are committed to developing MEMS/ NEMS systems [3].

Table 1. The possibilities of using nanoparticles depending on their properties

Property	
Volume:	
-Single magnetic domain	-Magnetic recorder
-Size more minuscule than the wavelength	-Absorption of light or heat
-Large and selective optical absorption of metal nanoparticles	-Colours, filters, solar absorbents, photovoltaic, photographic, and phototropic materials
-Formation of ultra-fine pores due to the surface congestion of nanoparticles	-Molecular filters
-Homogeneous mixture of different types of nanoparticles	-Research and development of new materials
-Smaller grain size than possible, stable dislocations	-High strength and hardness to metallic materials
Surface (interface):	
-Large specific surface	-Catalysis, sensors
-Large area, low heat capacity	-Heat exchange materials
-Low synthesizing temperature	-Synthesizer accelerators
-This interface is high	-Production of nanostructured materials
-Super-elastic behaviour of ceramics	-Plastic ceramic
-Cluster coatings	-Special resistors, temperature sensors
-Multilayer nanoparticles	-Very active catalysts

The term 'NEMS' or 'nanoelectromechanical systems' is used to describe devices that integrate mechanical and electrical functionality at a nano-scale. NEMS forms the next miniature logical step on MEMS devices.

NEMS typically integrates transistor-like nanoelectronics with mechanical actuators, pumps, or motors and therefore can form chemical, biological, and physical sensors.

The name is derived from typical device dimensions in the nanometer range, resulting in low mass mechanical resonance frequencies, high quantum mechanical effects such as zero-point motion, and a high surface-to-volume ratio for surface detection mechanisms. Applications include accelerometers or chemical detectors in the air [3], [4].

It relies on silicon nanowires, carbon nanotubes, piezoelectric and 2D materials, as well as on optical fabrication, electron beam lithography or thermal treatment.

Based on the above, the work will summarize both the central technology behind the achievement of the MEMS and NEMS components and the broad scope products, insisting on the applicability in the aero-astronautic field, exemplify the constructive features of accelerometric sensors and gyroscopic sensors. An overview on the latest developments in the technology and the materials used for MEMS/ NEMS components and various solutions for improving the performance is presented.

2. GENERAL PRODUCTION PROCESS

New technologies for making NEMS or MEMS electronic devices and circuits involve the use of new types of materials in the form of structures composed of different substances with special, natural or sintered properties.

At the basis of obtaining new types of structured materials are different phenomena and properties specific to their components, such as the piezoelectric effect, ferromagnetism properties, paramagnetism, electrostrictive effect or magnetostrictive effect, on the latter property based the construction of actuators and sensors.

Among the materials with a strong magnetic property is cobalt and among the alloys with the highest magnetostriction is Terphenol-D whose name indicates the composition of its structure (Ter de la Terbium, symbolized element TB, Fe – iron, NOL – Naval Ordnance Laboratory, D which comes from the element dysprosium, which is symbolized Dy).

MEMS-type structures are multilayer structures obtained by applying a sequence of surface processing and treatment technologies called micro processing technologies.

The materials used in the MEMS manufacture are of two types: materials used as substrate and deposition materials.

Silicon is the primary material used as a substrate in the manufacture of MEMS due to its characteristics: The property to form the type of crystal network specific to the diamond, to have a higher elasticity coefficient than steel, and its specific hardness, which exceeds the hardness of most metals.

After introducing silicon in the technological processes of obtaining MEMS devices, the size of the accelerometer has been significantly reduced compared to the existing devices so far. The miniaturization techniques have resulted in accelerometers and gyro measuring up to a few mm^3 [5].

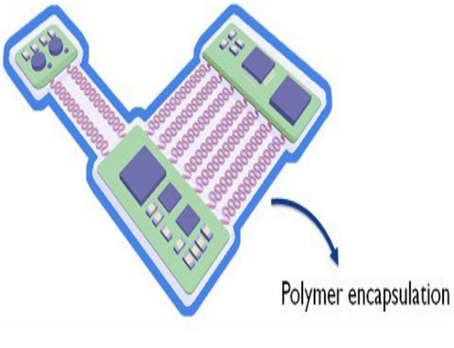

Fig. 2: Electronic microsystem with polymeric encapsulation [6]

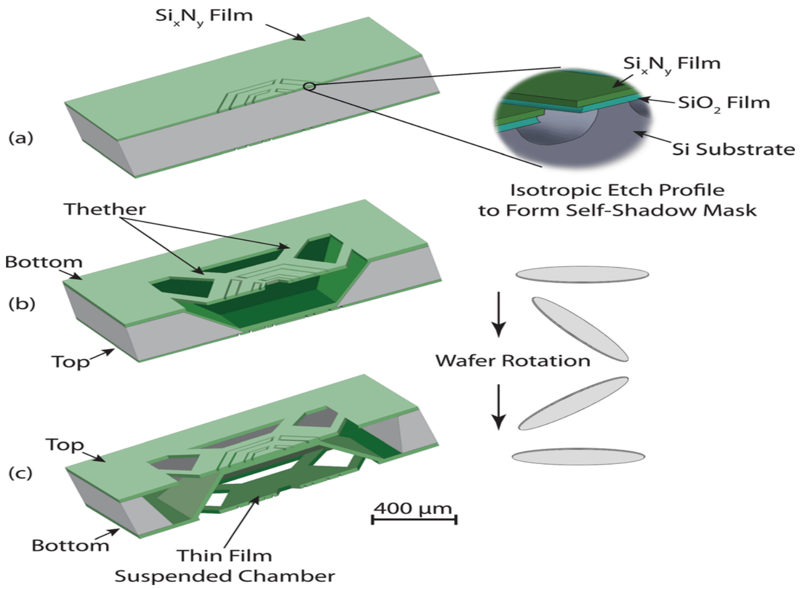

Fig. 3: Schematic illustration of the surface microprocessing process [7]

The main technological processes underlying MEMS-type structures' production are microprocessing technologies in volume and surface and LIGA microprocessing.

Microprocessing in volume characterizes microprocessing within the material, practically in its volume. It is based on the coating, lithography, and corrosion deposition processes. This microtechnology consists of obtaining components by corroding the basic structure, resulting in suspended mechanical structures.

While layering is a procedure used to obtain both independent structures and structures to be further processed, the lithography technique consists of a radiation beam's action to transfer the desired template to a photosensitive material layer.

When the photosensitive material is exposed to a radiation source, a change in its chemical resistance occurs. Finally, the erosion or deposit procedure will result in the desired configuration.

Corrosion is used as a process, both for modelling already deposited layers on a given surface and for materials used as a substrate.

The second microprocessing technology, i.e., surface microprocessing consists of processing layers of sacrifice, containing suspended structures of spring, leaf, or movable structures.

This microtechnology has the highest use in obtaining electronic detection and response devices, applicable to the construction of accelerometers or gyroscopic micro-level structures (Fig. 3).

Equally widespread with the technologies mentioned above is the LIGA technology, shown in Fig. 4.

The name comes from the abbreviation Lithographie Galvanoformung Abformung in German, being similar to the manufacturing processes microprocessors [8].

Last but not least, the hot printing process is part of the category of MEMS production technology.

This process consists of creating metal structures such as inserts, which are subsequently printed when hot in a polymer layer, making the desired piece (Fig. 5).

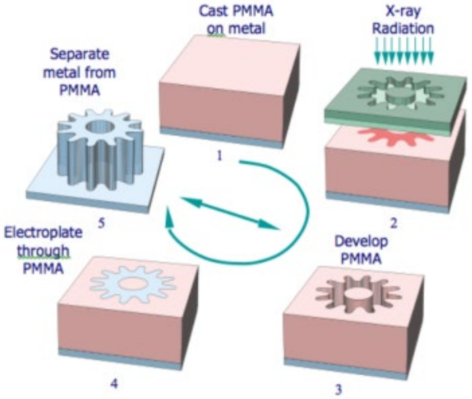

Fig. 4: Example of the product obtained by LIGA technology [9]

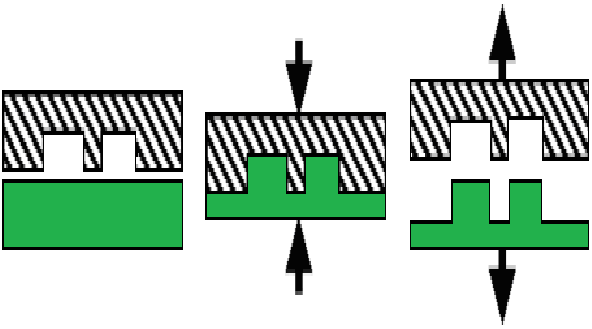

Fig. 5: Presentation of the steps in the print process [9]

3. APPLICATION AND GROWTH TRENDS

Nano-chemical materials and nanocomposites, which are characterized by ultra-fine grain size (below 50 nm), are of high scientific and commercial interest due to their particular mechanical, electrical, optical, and magnetic properties [10].

It has been experimentally demonstrated that various physical methods can be of nanoparticle size. In contrast, the effect of surface area size can be evidenced by measuring thermodynamic properties such as vapor pressure, specific heat, thermal conductivity, and metal particles' melting point.

It should be stressed that due to the small size, any surface coverage of nanoparticles has a strong influence on their properties.

Each of the two types of size effects has been clearly distinguished in the studies carried out on the optical properties of composite in metal clusters.

Among other examples of the effects of particle size, it is noted that the same electrical conductivity of epoxy resins with silver filling can be obtained with a smaller and smaller metal content as the particles used as packing material fall below 100 nm.

Tiny semiconductors (less than 10 nm), glass-metal composite, and semiconductor-polymer composites have interesting non-linear optical and electrical properties.

These technologies for nanocomponents and micro-components are increasingly being used to achieve NEMS or MEMS-type structures.

Given the microscopic dimensions and qualities of nanoelectromechanical and microelectromechanical components, they are increasingly used in industry-leading, with broad applications in the aerospace industry.

The technologies used in the manufacture of MEMS are mainly used in the manufacture of sensors.

Of particular importance in this regard is the manufacture of the necessary gyrometers and accelerometers in aviation.

4. EXPERIMENTAL PROCEDURES AND PRACTICAL ACHIEVEMENTS

As mentioned above, MEMS or NEMS architectures are widely used in various branches of industry, including aeronautics such as in the manufacture of inertial navigation systems, this category includes both gyroscopic and accelerometric sensors.

Gyroscopes are basically those electromechanical components that rotate around their own axis of rotation at very high speed, experiencing minimal resistance from friction forces. For their integration into the category of complex measuring systems, gyroscopes may be implemented with 1, 2 or more degrees of freedom materialized in the possibility of their rotation around axes perpendicular to their own axis of rotation.

Gyroscopes used in the inertial navigation system are characterized by low bias values due to the fact that they have temperature-dependent components in the structure.

Thus, each gyroscope is characterized by the existence in its composition of a temperature sensor. Thus, in order to determine the variation of the temperature function bias, the manufacturers of inertial gyroscopes must perform a series of tests under different conditions to obtain a mathematical model that achieves this dependence. Testing involves the use of a test chamber that allows accurate temperature control.

The principle of testing is to rotate the gyroscope at constant angular speed at constant temperature so that the influence of noise can be eliminated for a large number of readings over a given time interval.

The operation is repeated for different temperature values but keeping the angular speed value constant.

Accelerometric sensors are based on the displacement of a mass under the action of inertia forces. The accelerometer can be used in two measuring ranges ±1.5g or ±6g.

The graphical representation of the experimental data obtained through averanging and evaluation of temperature errors for each node of the testing grid, for accelerometer on x-axis, is shown in Fig. 6; the left part of the figure shows the error surface generated as a function of the acceleration sensed by the accelerometer and of the temperature at which it works. Also, an example of recordings obtained at null inputs (0g), corresponding to the temperature of 50°C, is depicted in Fig. 7.

If accelerometric sensors are based on a local linear displacement of a mass under the action of inertial forces, gyroscopic sensors are based on the law of conservation of angular momentum or the law of rotation inertia, based on which the total kinetic moment of the gyroscopic system remains constant as long as the sum of the external disturbing moments is zero.

The use of alternative inertial gyroscopes testing methods as well as mathematical simulation of the obtained results aims to effectively address solutions aimed at improving the accuracy of accelerometers and gyrometric sensors.

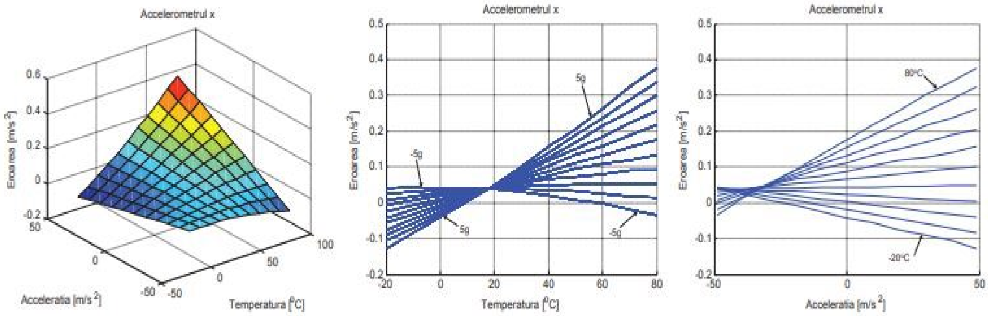

Fig. 6: Experimental data obtained for accelerometer on x-axis [11]

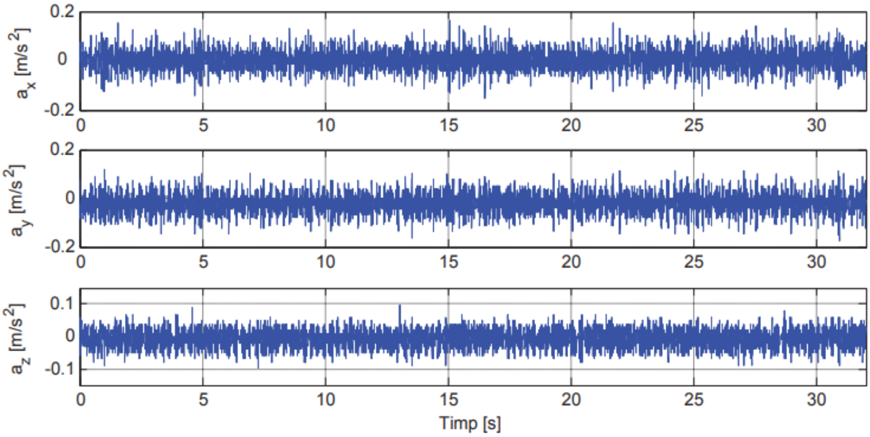

Fig. 7: Recordings obtained at null inputs and 50°C [11]

Among the types of gyroscopes, the MEMS vibratory gyroscopes are currently a mature technology and also the most employed.

These use the Coriolis force in order to measure the angular velocity of a vibrating mechanical element considered as the sensing element. Based on the transduction type, it can be classified as:

a) *Silicon or quartz tuning fork*: is the preeminent configuration group. It relies on two proof-masses that are electrostatically driven in order to oscillate with equal amplitude but in opposite directions. Thus, the Coriolis force will create a vibration sensed by electrostatic drive electrodes when the device is rotated.

A variety of tuning fork MEMS gyroscopes have been proposed over the years, attaining good performances, with various solutions presented in order to improve the performance. Utilizing nickel-electroforming technology, single crystal silicon on glass and polysilicon, the first architecture was proposed in 1993.

In [12] an x-axis tuning fork gyroscope with “8 vertical springs-proof mass” structure is presented. This configuration allows to suspend the large thick proofmass, having large capacitance variation and low mechanical noise. It is fabricated by using bulk micromachining processes, starting with a 350µm-thick low-resistivity (111)-silicon wafer, technology also used in developing a gyroscope working at atmospheric pressure with high Q-factors [13], presented in Fig. 8. This technology uses two oscillating frames with bar structure proof masses, being able to move in the x or y direction and the slide-film damping in the gap between proof masses and glass substrate helps in eliminating the vacuum packaging.

Also, using silicon-glass bonding and deep reactive ion-etching (DRIE) technology (Fig. 9), a gyroscope that can operate at atmospheric pressure by electrostatic driving and capacitive sensing was introduced in [14].

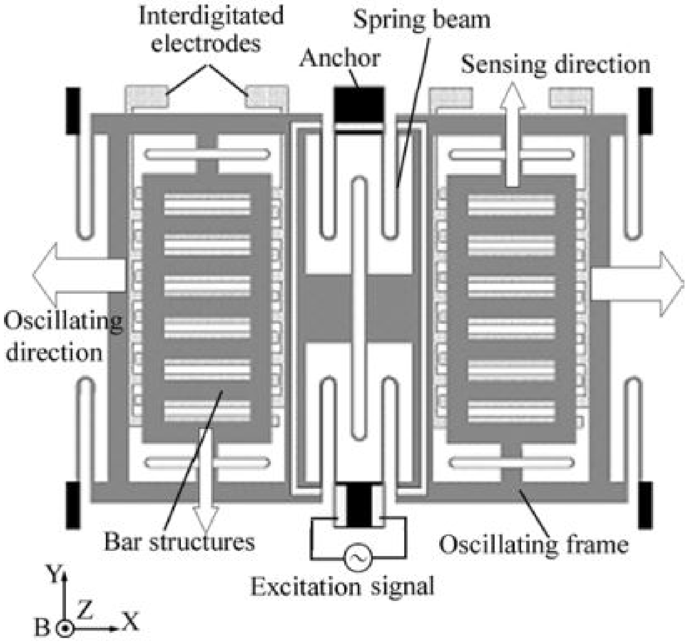

Fig. 8: Schematic tuning fork gyroscope [13]

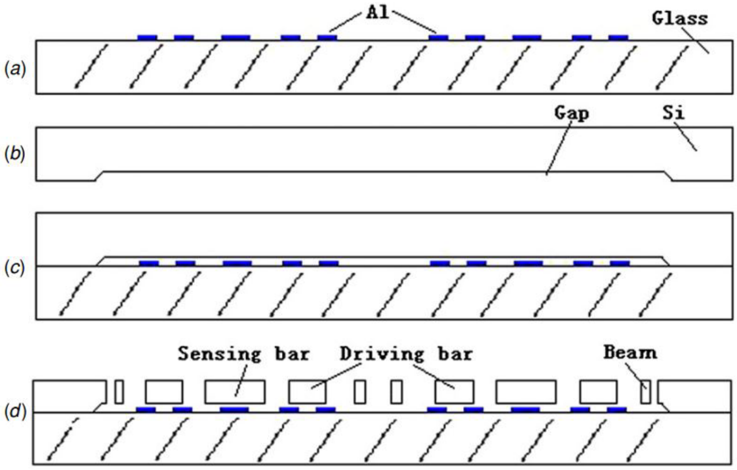

Fig. 9: Fabrication process [14]

Using a 40μm SOI wafers, an in-plane solid-mass silicon tuning fork gyro was designed in [15], using a two-mask process.

It shows high sense mode quality factors, large drive amplitudes and increased mass, achieving better angular rate resolutions. In [16] a gyroscope with anchored coupling mechanism is proposed.

Using an anchored coupling ring spring connected by four linear beams, it has a lower vibration output, improving the overall performance.

Further, this solution is improved by utilising an anchored diamond coupling mechanism which optimizes the sense-mode through [17].

By using a using a standard silicon-on-insulator technology, a 3-axis gyroscope is introduced in [18]. With small adaptations to an out-of-plane sensitive gyroscope (z-axis), the x and y axes are realized on chip.

In order to realize the out-of-plane oscillations, the solution with torsion mode of unthinned beams is employed. Because this generates a high non-linearity of the out-of-plane oscillation due to the hardening spring phenomenon, it is introduced a folded beam configuration, but such architecture can lead to drive mode complexity and more power consumption. The fabrication of adapted SOI technology is illustrated in Fig. 10.

In [19], a split-mode MEMS gyroscope with a CMOS readout circuit is presented, having as application indoor navigation or UAV. By using reduced quadrature coupling and thermoelastic damping, the sensing element is optimized, supressing the circuit noise. The low-noise charge sensitive amplifier along with a phase-sensitive demodulation helps in improving the angle random walk and the bias instability properties.

By means of quartz anisotropic wet etching process, a z-axis quartz gyroscope is proposed in [20] (Fig. 11). A shear stress detection scheme helps on simplifying the sidewall electrodes, obtaining a quality factor in air of 7600.

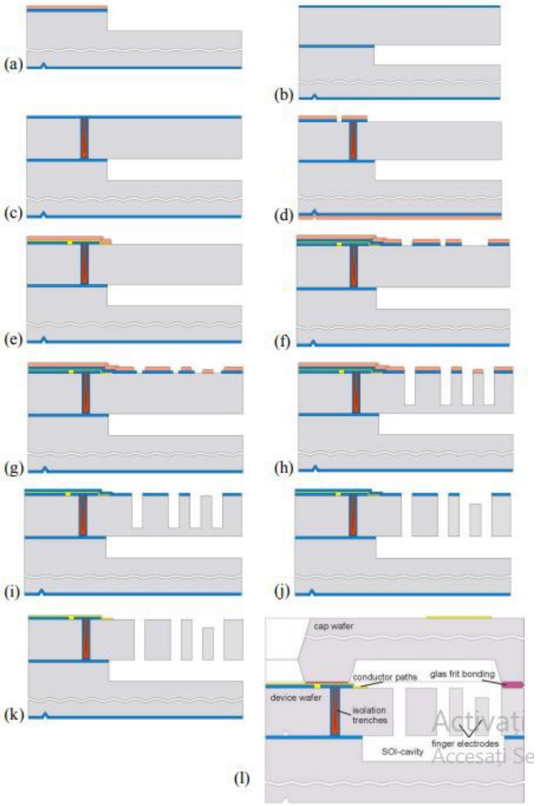

Fig. 10: Process flow for multi-axis sensing elements [18]

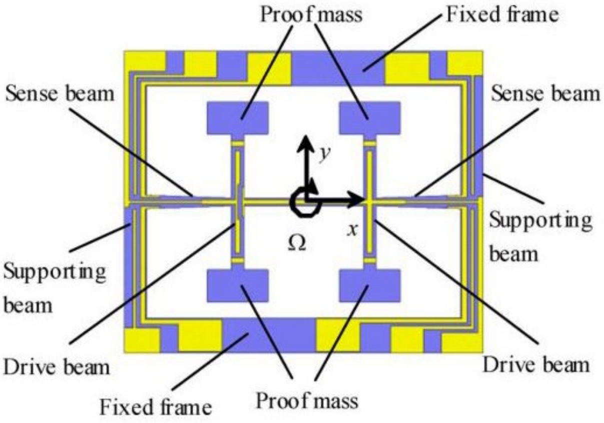

Fig. 11: Gyroscope's structure [20]

b) *Vibratory ring*: consists in a symmetrical structure, such as ring, cylinder, hemisphere, that is slightly affected by ambient temperature and vibration. However, as the structure has a low vibrating mass it can result in low sensitivity.

A first version of a vibratory ring MEMS gyroscope was proposed in 1994, using silicon surface micromachining [21], being further improved in [22] by increasing the vibrating mass and sense capacitance, using (111) oriented single-crystal silicon, a vibrating ring of 2.7 mm diameter and support springs designed as meander-shaped. Although through a simple fabrication process, it shows high Q, good nonlinearity, large sensitivity and high resolution.

In [23] a gyroscope with a highly symmetric structure is introduced, using eight "M" type beams, four drive electrodes and four sense electrodes, which support the 4mm diameter ring (Fig. 12). It is fabricated by bulk silicon processes on a single crystal silicon wafer, starting with the thermal oxidation and the deposition of SiN as the transition layer. The last step is represented by the deep reactive ion etching process. After the test, it is proved it can have good performance under harsh conditions.

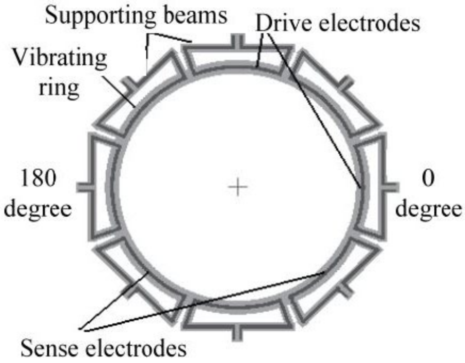

Fig. 12: Schematic diagram of symmetric structure gyroscope [23]

Using a hinge-frame mechanism, a new micromachined vibrating ring gyroscope is presented in [24]. Through the combination hinge and variable-area capacitance strategy, it shows good results in terms of the quadrature error and high-linearity.

In [25] it is introduced the resonating star gyroscope, using the single-wafer high aspect-ratio combined poly and single-crystal silicon (HARPSS) fabrication technology. HARPPS is an all-silicon process that uses a layer of low-pressure chemical vapor deposited (LPCVD) silicon nitride, one layer of LPCVD silicon dioxide, and one layer of LPCVD polysilicon [26]. It uses a trench-refilled polysilicon beams method and a deep dry-release thick silicon microstructures from the substrate, providing features required for high-performance inertial sensors such as improving the long-term stability and temperature sensitivity.

c) *Vibratory disk:* it is based on a disk-shaped proof-mass that will vibrate around its axis of symmetry.

In [27] is presented a disk resonator gyroscope with a high-quality factor and long decaying time constant. It is fabricated using as substrate a P-type 500-µm (111) single-crystal silicon wafer and a SOI wafer with a 150-µm (111) single-crystal silicon device layer. However, the performance of the gyroscope can be limited by the readout electronics.

The micro electro-mechanical system technology has also been combined with the other categories of gyroscopes such as piezoelectric vibrating gyroscopes, thermal convective gyroscopes, micro-gyroscopes based on levitation effect, micro-gyroscope based on the Sagnac effect, atom gyroscopes and micro-gyroscopes based on nuclear magnetic resonance [28], however the technology is not mature enough [29].

The piezoelectric vibrating gyroscopes have as advantage a high reliability and sensibility in no-vacuum package, with a higher resistance to outer shock and shake. In [30] a device with a promising simple structure, consisting of a prism-shaped bulk-PZT (Lead Zirconate Titanate: piezoelectric material) was presented, using a formation of electrodes and dicing and the 29th resonance mode as the reference vibration. The structure is improved in [31], several configurations with single-axis and double axis gyroscopes being proposed.

In an ideal mode of operation, the vibrating modes of the gyroscope should be un-coupled, but in practice, due to the fabrication and environment variations, a mismatch can appear and it can cause a false output. In order to improve the stability of MEMS gyroscope and to get an accurate value of the angular rate, control loops are used, such as automatic gain control and phase-locked loop [32], $H\infty$ synthesis [33], adaptive control based on global terminal sliding mode controller [34], model predictive control [35].

In order to assess the performance of a gyroscope, the following parameters are mentioned: the zero-rate output, the range, the sensitivity and the bias drift. The zero rate output represents the signal when no angular velocity is applied, being affected by the quadrature compensation, synchronous demodulation or environment. These characteristics can be influenced by the random noise that can appear because of the machining inaccuracies, temperature or other sources. Thus, these errors must be supressed by improving the structure of the MEMS gyroscope or by designing an algorithm which can eliminate the noise in software. In the specific literature several solutions can be found such as using Kalman filter [36],Wavelet De-noising [37], Allan Variance [38] or Auto-Regressive [39] methods. Also, artificial intelligence can provide benefits in terms of handling complex data, process optimization, product improvement, fault diagnosis and detection and drift compensation with its limitations when applied in industrial settings [40].

The MEMS gyroscopes can have the micromechanical and electronic components on a single chip or an on two separate chips.

On a single chip it has the advantage of a reduces size, but the two-chip implementation can allow a better control on the fabrication processes.

In order to verify the integrity of these devices, it should go through MEMS reliability identification processes [41].

These processes imply testing the material properties, an environmental verification which includes acoustic noise, random vibrations and finding the failure modes. As withstanding the surface interactions is a major problem in designing MEMS and can lead to failure, a stiction test must be carried out.

Also, a quite common problem comes from the radiation from other sources that can make the materials more susceptible to fracture, phenomenon called displacement damage, thus the radiation effects must be studied. In the case of space applications, some tests may be repeated to check the validity of the devices for the launch environment.

5. CONCLUSIONS

Considering the developing aerospace industry market, the fabrication of NEMS or MEMS components with high precision in low-cost mass production is a constant need, as well as improving their performance, especially in the field of unmanned aerial systems (UAS) where the constraints related to weight, size and power consumption are much tougher.

During this work, the technologies for obtaining these devices, such as microprocessing in volume and surface and LIGA microprocessing were discussed and various accelerometers and gyroscope principles were presented.

Starting from the first micro gyroscopes produced in 1980, various solutions were reviewed, considering the fabrication process, in terms of bulk micromachining, HARPSS or SOI, materials (polysilicon, single crystal silicon), structure (different configuration architecture) and control technologies. As the silicon technology became more mature and different studies were made considering both the theoretical and practical aspects of MEMS/NEMS, the performance has improved. Also, the reliability of MEMS devices in real working conditions is discussed, the lower stiffness specific to these leading to fragility in the shock environment. The applicability in the aerospace field was considered, describing the construction and functionality principles.

ACKNOWLEDGEMENTS

This work has been funded by the European Social Fund from the Sectoral Operational Programme Human Capital 2014-2020, through the Financial Agreement with the title "Training of PhD students and postdoctoral researchers in order to acquire applied research skills - SMART", Contract no. 13530/16.06.2022 - SMIS code: 153734.

REFERENCES

[1] N. Taniguchi, *Nanotehnologie. Sisteme de procesare integrată pentru produse ultrafine şi de ultraprecizie*, Bucureşti: Editura Tehnică, 2000.

[2] S. Mustață, *Materiale și tehnologii cu destinație specială*, I. 978-973-640-306-4, București: Editura Academiei Tehnice Militare “Ferdinand I”, 2019.

[3] Jack W. Plunkett, *Plunkett's Nanotechnology & MEMS Industry Almanac 2017: Nanotechnology & MEMS Industry Market Research, Statistics, Trends & Leading Companies*, Plunkett Research, 2017.

[4] M. Kraft, Micromachined inertial sensors: The state of the art and a look into the future, *IMC Measurement and Control,* vol. **33**, 2000.

[5] J. Li, D. Powell, S. Getty and Y. Lu, High Sensitivity, *Low Power Nano Sensors and Devices for Chemical Sensing*, Goddard Space Flight Center, Greenbelt, MD, 2004.

[6] * * * Available at : https://www.cmst.be/groups/stretchablemicrosystems.html.

[7] B. Davaji, H. J. Baki, W.-J. Changi and C. H. Lee, A novel on-chip three-dimensional micromachined calorimeter with fully enclosed and suspended thin-film chamber for thermal characterization of liquid samples, *Biomicrofluidics,* vol. **8**, no. 3, 2014.

[8] V. Saile, U. Wallrabe, O. Tabata, J. K. (. eds.), O. Brand, G. Fedder, C. Hierold, J. Korvink and O. Tabata (eds.), *LIGA and its Applications, Advanced Micro & Nanosystems*, vol. 7, Weinheim, Germany: WILEY-VCH, 200.

[9] * * * Available at: https://www.mems-exchange.org/MEMS/fabrication.html

[10] M. Sen, Nanocomposite Materials, *Nanotechnology and the Environment,* 2020.

[11] T. Grigorie, I. Corcau and A. Tudosie, Identification and compensation of the temperatures influences in a miniature three-axial accelerometer based on the least squares method, in *AIP Conference Proceedings*, 2017

[12] Fei Duan, Yuncai Wang, Ying Zhang, Benwei Me, Jinpeng Li, Jian Zhu A Novel X-Axis Tuning Fork Gyroscope With "8 Vertical Springs–Proofmass" Structure On (111) Silicon, *Microsyst Technol,* vol. **14**, p. 1009–1013, 2008.

[13] Y. Chen, J. Jiao, L. Xiong, B. Che, Y. Li and X. Wang, A novel tuning fork gyroscope with high Q-factors working at atmospheric pressure, *Microsystem. Technol.,* vol. **11**, p. 111–116, 2005.

[14] L. Che, B. Xiong, Y. Li and Y. Wang, A novel electrostatic-driven tuning fork micromachined gyroscope with a bar structure operating at atmospheric pressure, *J. Micromech. Microeng.,* vol. **20**, p. 015025, 2009.

[15] M. Zaman, A. Sharma, B. Amini and F. Ayazi, Towards Inertial Grade Vibratory Microgyros: A High-Q in-Plane Silicon-on-Insulator Tuning Fork Device, in *Proceedings of Solid-State Sensor, Actuator and Microsystems Workshop*, Hilton Head Island, SC, USA, June 2004.

[16] Y. Guan, S. Gao, L. Jin and L. Cao, Design and vibration sensitivity of a MEMS tuning fork gyroscope with anchored coupling mechanism, *Microsyst. Technol.,* vol. **22**, p. 247–254, 2015.

[17] Y. Guan, S. Gao, H. Liu and L. N. S. Jin, Design and Vibration Sensitivity Analysis of a MEMS Tuning Fork Gyroscope with an Anchored Diamond Coupling Mechanism., *Sensors,* vol. **16**, no. 4, p. 468, 2016.

[18] M. Traechtler, T. Link, J. Dehnert, P. Nommensen and Y. Manoli, Novel 3-Axis Gyroscope on A Single Chip Using SOI-Technology, in *Proceedings of the IEEE Conference on Sensors*, Atlanta, GA, USA, 28–31 October 2007.

[19] X. Wu, L. Xie, J. Xing, P. Dong, H. Wang and J. Su, A z-axis quartz tuning fork micromachined gyroscope based on shear stress detection, *IEEE Sens. J.,* vol. **12**, p. 1246–1252, 2012.

[20] J. Wang, L. Chen, M. Zhang and D. Chen, A Micromachined Vibrating Ring Gyroscope with Highly Symmetric Structure for Harsh Environment, in *Proceedings of the 5th IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, Xiamen, China, 20–23 January 2010.

[21] Y. Zhao, J. Zhao, X. Wang, G. Xia, Q. Shi, A. Qiu and Y. Xu, A Sub-0.1°/h Bias-Instability Split-Mode MEMS Gyroscope With CMOS Readout Circuit, *IEEE J. Solid-State Circuits,* vol. **53**, p. 2636–2650, 2018.

[22] M. W. Putty and K. Najafi, A micromachined vibrating ring gyroscope, in *Digest, Solid-state Sensors and Actuators Workshop*, Hilton Head, SC, 1994.

[23] K. N. Guohong He, A single-crystal silicon vibrating ring gyroscop, în *echnical Digest. MEMS 2002 IEEE International Conference. Fifteenth IEEE International Conference on Micro Electro Mechanical Systems (Cat. No.02CH37266),* Las Vegas, NV, USA, 2002.

[24] Z. Li, S. Gao, L. Jin, H. Liu and S. Niu, Micromachined Vibrating Ring Gyroscope Architecture with High-Linearity, Low Quadrature Error and Improved Mode Ordering, *Sensors,* vol. **20**, no. 15, p. 4327, 2020.

[25] F. Zaman, A. Sharma, V. Amini and F. Ayazi, The Resonating Star Gyroscope, in *Proceedings of the 18th IEEE International Conference on Micro Electro MEMS*, Miami, FL, USA, 30 January–3 February 2005.

[26] F. Ayazi and K. Najafi, A High-Aspect Ratio Combined Poly and Single-Crystal Silicon (HARPSS) MEMS Technology, *IEEE/ASME JMEMS,* pp. 288-294, September 2000.

[27] Q. Li, D. Xiao, X. Zhou and e. al., 0.04 degree-per-hour MEMS disk resonator gyroscope with high-quality factor (510 k) and long decaying time constant, *Microsyst Nanoeng,* vol. **4**, p. 32, 2018.

[28] M. N. Armenise, C. Ciminelli, F. Dell'Olio and V. M. N. Passaro, *Advances in Gyroscope Technologies*, Berlin/Heidelberg, Germany: Springer, 2010

[29] D. Xia, C. Yu and L. Kong, The development of micromachined gyroscope structure and circuitry technology, *Sensors (Basel),* vol. **14**, no. 1, p. 1394–1473, 2014.

[30] K. Maenaka, H. Kohara and M. Nishimura, Solid Micro-Gyroscope, in *Novel Proceedings of the IEEE Conference on MEMS*, Istanbul, Turkey, 22–26 January 2006.

[31] Y. Lu, X. Wu, W. Zhang, W. Chen, F. Cui and W. Liu, Optimization and analysis of novel piezoelectric solid micro-gyroscope with high resistance to shock., *Microsyst. Technol.,* vol. **16**, p. 571–584, 2010.

[32] T. Perl, R. Maimon, S. Krylov and N. Shimkin, Control of Vibratory MEMS Gyroscope With the Drive Mode Excited Through Parametric Resonance, *ASME. J. Vib. Acoust.,* vol. **143**, no. 5, p. 051013 (11 pages), October 2021.

[33] F. Saggini, C. Pernini, A. Korniienkoi, G. Scorlettii and C. L. Blanc, Digital Control of MEMS Gyroscopes: a Robust Approach, in *2021 IEEE International Symposium on Inertial Sensors and Systems (INERTIAL)*, Kailua-Kona, HI, USA, Mar 2021.

[34] J. F. Weifeng Yan, Adaptive Control of MEMS Gyroscope Based on Global Terminal Sliding Mode Controller, *Mathematical Problems in Engineering,* vol. **2013**, 2013.

[35] M. H. Pishrobat and J. Keighobadi., Model Predictive Control of MEMS Vibratory Gyroscope, in *The International Federation of Automatic Control*, Cape Town, South Africa, 2014.

[36] S. Cai, Y. Hu, H. Ding and H. Chen, A Noise Reduction Method for MEMS Gyroscope Based on Direct Modeling and Kalman Filter, *IFAC-PapersOnLine,* vol. **51**, no. 31, pp. 172-176, 2018.

[37] I.-R. Edu, F.-C. Adochiei, R. Obreja, C. Rotaru și T. L. Grigorie, Inertial Sensor Signals Denoising with Wavelet Transform, *INCAS BULLETIN,* vol. **7**, nr. 1, 2015.

[38] Y. Zhang, S. Guo, Q. Chen, L. Han and Q. Si, Noise Identification and Analysis in MEMS Sensors Using an Optimized Variable Step Allan variance, *2019 Chinese Control Conference (CCC),* pp. 6309-6314, 2019.

[39] M. Ding, Z. Shi, B. Du, H. Wang, L. Han and Z. Cheng, The method of MEMS gyroscope random error compensation based on ARMA, *Measurement Science and Technology,* vol. **32**, no. 12, 2021.

[40] I. Podder, T. Fischl and U. Bub, Artificial Intelligence Applications for MEMS-Based Sensors, *Telecom,* vol. **4**, no. 1, pp. 165-197, 2023.

[41] S. Kayali, R. Lawton and B. Stark, *MEMS Reliability Assurance Activities at JPL*, 1999.