Nonconventional Technologies Review
Romania, September, 2019

LITHOGRAPHIC TECHNOLOGIES FOR SUBMICRONIC PATTERNS DESIGN APPLIED IN MICROSENSORS DOMAIN

Liliana-Laura Badita[1], Gheorghe Gheorghe[2], Valentin Gornoava[3] and Aurel Zapciu[4]
[1] National Institute of Research and Development for Mechatronics and Measurement Technique, badita_l@yahoo.com
[2] National Institute of Research and Development for Mechatronics and Measurement Technique, geocefin@yahoo.com
[3] National Institute of Research and Development for Mechatronics and Measurement Technique, valentin_gornoava@yahoo.com
[4] National Institute of Research and Development for Mechatronics and Measurement Technique, zapciu.aurel@yahoo.com

ABSTRACT: The present article is based on the results of a project that had as main objective to achieve submicronic patterns using different lithography techniques - electron beam lithography and atomic force microscopy lithography. Ways to obtain these patterns were tested on silicon and copper substrates, following their use for designing and experimenting of microsensors models. Predefined complex geometric shapes of the patterns could be fully realized using electron beam lithography on the tested substrates. Submicronic patterns simpler compared to those obtained by electron beam lithography were realized using atomic force microscopy lithography on both substrates' types. Also, based on the atomic force microscopy analysis and the determination of the tribological parameters (e.g. average roughness, surface skewness, coefficient of kurtosis, average profiles) of the surfaces it was demonstrated that patterns with nano-scale depth were obtained using both types of lithography. Following the obtained results, it was concluded that from the two techniques used, electron beam lithography allowed to obtain more complex submicronic patterns. In the future, these will be used to design microsensors integrated in mechatronic and cyber-mixmechatronic systems and microsystems.

KEY WORDS: submicronic patterns, electron beam lithography, atomic force microscopy lithography, microsensors, mechatronics, cyber-mechatronics

1. INTRODUCTION

Microsensors are continuously developing and find applications in different domains of industrial environments, like machines manufacturing, mechatronics, fine mechanics, electronics, aerospace industry, iron and steel industry, metallurgy etc. [1], [2].

The sensor transforms a variation of a mechanical or other nature size into a variation of electrical size. In this way, it can measure variations of different mechanical sizes: forces, torques, pressures, linear or angular displacements, speeds, accelerations etc. (Figure 1) [3], [4].

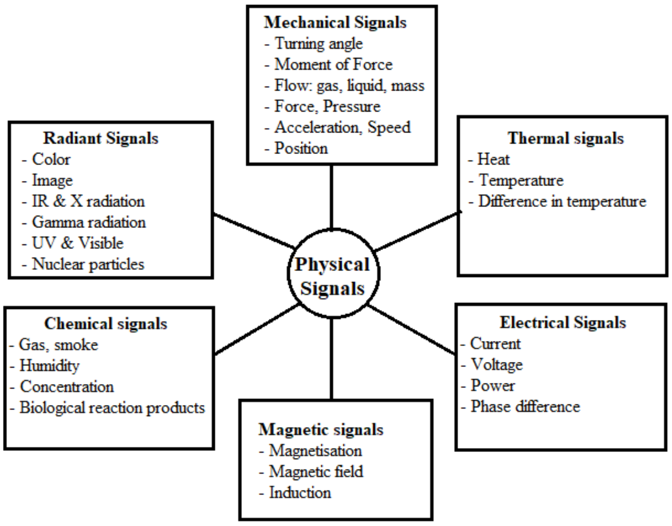


Figure 1. Types of sizes that can be transformed by transducers into measurable physical signals [3]

The sensor provides an electrical signal proportional to the intensity of the measure of which variation is monitored. For this reason, a sensor comprises in its structure a transducer for converting the input to a useful electrical signal. This signal can be processed by measuring instruments or computers, as well as circuits for adapting and converting signals and, eventually, for processing and evaluating information.

Sensors are classified according to several criteria, like: the signals they measure [5], the type of the input physical quantity, the type of output quantity, the number of transducers and the number of dimensions assigned to the measured values [6]. In Table 1 are shown the main types of sensors classified according to the signals they measure [5].

The first micro and nanosensors have been developed on a mature infrastructure made of Si built for the integrated circuit industry (IC). Recently, the main materials used to produce sensors are: carbon nanotubes, graphene, nanowires and nanocrystals, conductive polymers, silicon-based materials, germanium-based materials, metals (e.g. aluminium, gold, chrome, titanium), severe semiconductors (e.g. silicon carbide, diamond, gallium arsenic) and piezoelectric materials (e.g. lead zirconium titanate) [7].

Table 1. Classification of sensors according to the signals they measure

Signal's shape	Measured sizes
Thermal	Temperature, heat, heat flow, entropy, heat capacity etc.
Radiant	Gamma rays, x-rays, ultraviolet, visible and infrared light, microwaves, radio waves etc.
Mechanical	Displacement, speed, acceleration, force. Pressure, mass flow, amplitude and acoustic wavelength etc.
Magnetic	Magnetic field, flow, magnetic moment, magnetization, magnetic permeability etc.
Chemical	Humidity, pH level and ions, gas concentration, toxic and flammable materials, vapours and odours concentration, pollutants etc.
Biological	Sugars, proteins, hormones, antigens etc.

Using these materials, different techniques that involve the creation of nanostructures by different technologies are used today to produce sensors [8]: lithography; silicon processing by anisotropic corrosion; LIGA (consisting of lithography, galvanic deposition of layers and formation); SOI manufacturing techniques by implantation or deposition.

Lithography consists of transferring a pattern from a template (physical or virtual mask) to a substrate made of various materials (metal, nitride, oxide, silicon, glass, GaAs etc.). This pattern is then used to engrave a thin base film (such as an oxide or a nitrate) for different purposes [9]. The main types of lithography are: photolithography, optical lithography, electron beam/ ion beam lithography, nanoimprint lithography, X-rays lithography, Scanning Probe Lithography, etching [10], [11], [12], [13], [14]. Electron beam lithography can define high resolution nanostructured patterns (~ 10nm) and over large areas (> 1cm^2). It uses an electron beam accelerated at a medium of 5kV to 100kV to expose a substrate coated with electron-resist [12]. The electron beam allows direct patterning without the need for pre-existing masks. Electron-resists are the environment on which irradiation produced by the electron beam and a subsequent development turn it into a mask for transferring a pattern on the working substrate of a configuration. The electron beam that exposes the electron-resist is made of electrons accelerated at voltages of kilovolts order. When these electrons enter the sample, they interact with the electric fields of the sample atoms. The electrons in the beam can undergo elastic scatterings altering their movement direction, and after a certain number of deflections, these electrons can even return backward leaving the sample.

Scanning Probe Lithography is a technique in which microscopic systems are used. These systems use a combination of atomic force microscopy (AFM) and scanning tunnelling microscopy (STM) modes: the tip is mounted in a cantilever with electrical connection so that the surface force and the tunnelling current are controlled or monitored. Atomic force microscopy (AFM) uses a microscope with a proven sub-nanometric resolution in which the image is acquired by recording the vertical deflection of a cantilever using a laser and a photosensitive diode. Force lithography and electric lithography are important within AFM lithography. Force lithography is based on the direct mechanical impact produced by a thin measuring tip on the surface of the sample. Pressure of the tip of the measuring head is sufficient to cause plastic deformation on the surface of the substrate. Electrical lithography is based on the effect produced by the electric field in the contact area between the tip of the measuring head and the sample surface. When a potential is applied it generates the flowing of an electrons current between the thin measuring head and the sample. The electrical impact may be sufficient to cause local surface change.

Based on the importance of sensors in mechatronics and other industrial domains, the authors realized a project whose main objective was to achieve submicronic patterns using different lithography techniques that can be applied in the future in sensors domain.

2. EXPERIMENTAL METHODS

Submicronic patterns that could be used to manufacture sensors integrated in cyber-mechatronic systems have been developed using electron beam lithography and AFM lithography.

Electron beam lithography was realized using an installation that consist of a scanning electron microscope Zeiss Merlin Compact, having a laser interferometry nanolithography system with a resolution of up to 2 nm, from Raith.

Of all AFM lithography categories, AFM force lithography was applied to achieve submicronic patterns using an NTEGRA Probe NanoLaboratory NT-MDT Microscope.

Using these two lithographic techniques, submicronic patterns with predefined geometric shapes designed with the SolidWorks program (Figure 6) were printed on silicon and copper substrates. The copper substrate is a thin film with a thickness of 35 μm.

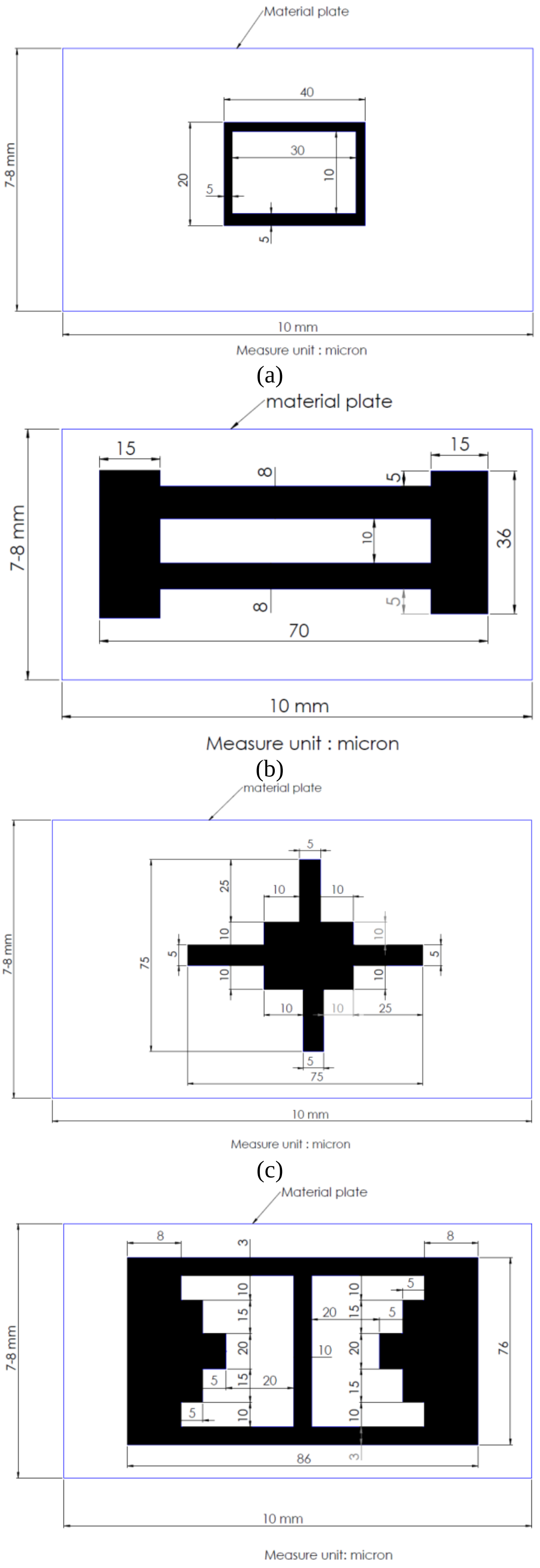


Figure 6. Predefined geometric shapes designed to make submicronic patterns using lithography techniques.

All the obtained submicronic patterns were analysed by atomic force microscopy using the NTEGRA Probe NanoLaboratory NT-MDT microscope.

3. RESULTS

Predefined complex geometric shapes of the patterns were fully realized using electron beam lithography on the substrates. The four predefined geometric shapes printed using the electron beam lithography on the Si substrate are presented in Figure 7.

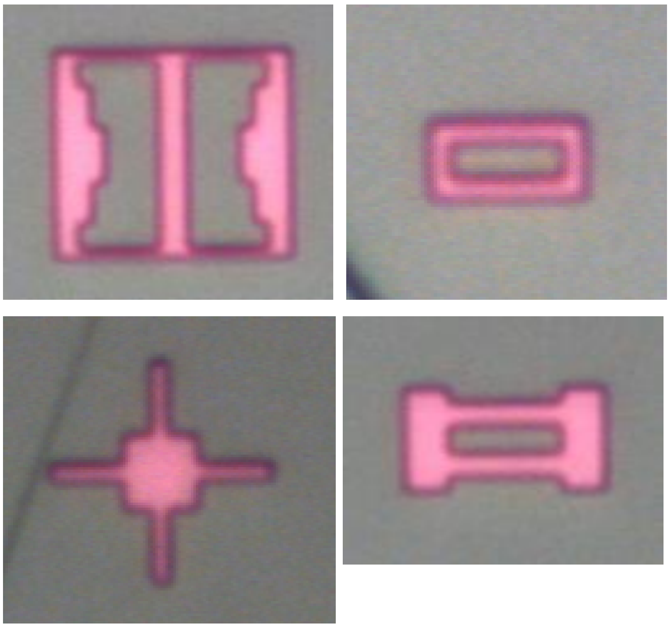
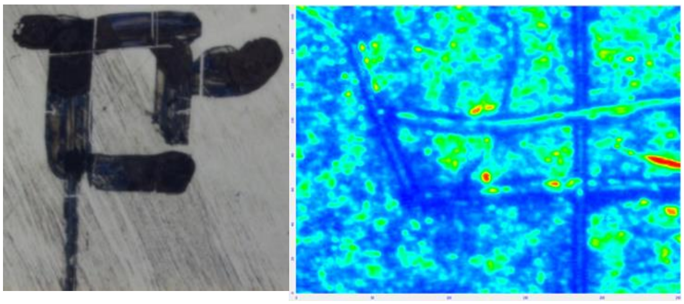


Figure 7. Micrometric patterns printed on Si substrate using electron beam lithography

All these submicronic patterns were analysed after finalization and it was observed that, in the case of Si samples processed by electron beam lithography, the dimensions of the patterns obtained were very close to those of the designed forms.

Using AFM force lithography, simpler geometric submicronic patterns (Figure 8) have been achieved.



(a) (b)

Figure 8. Micrometric pattern printed on Si substrate (a) and on Cu thin film substrate (b) using AFM force lithography

The obtained submicronic patterns were analysed using atomic force microscopy. Few samples obtained by electron beam lithography on Si substrate are presented in Table 2.

Submicronic patterns obtained by AFM force lithography on both substrate types - Si and thin Cu layer are shown in Table 3.

Table 2. AFM analysis of submicronic patterns produced by electron beam lithography on Si substrate

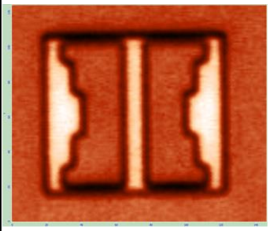
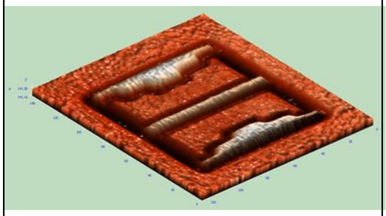
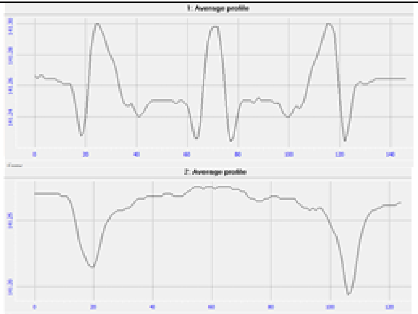
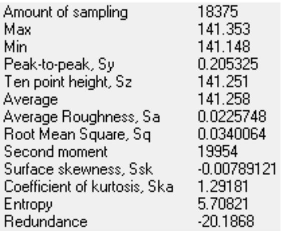
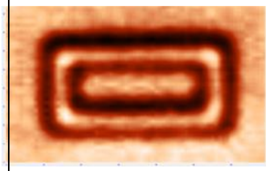
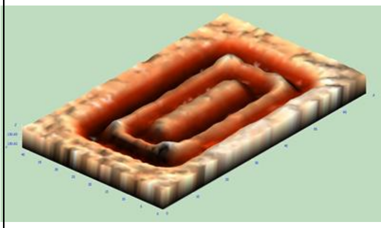
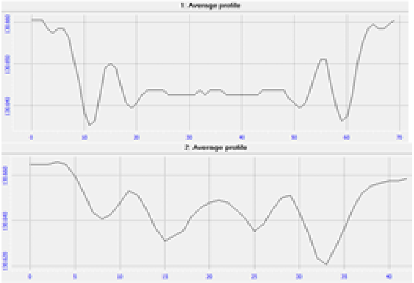
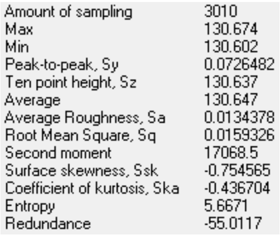
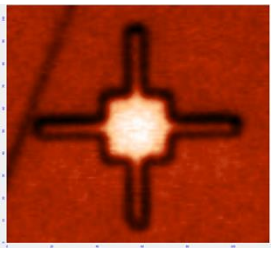
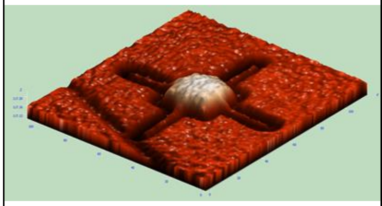
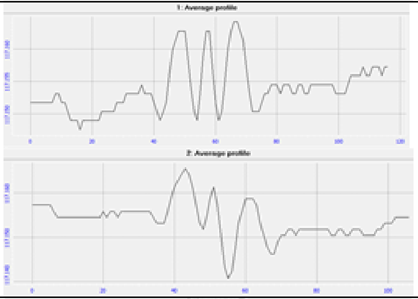
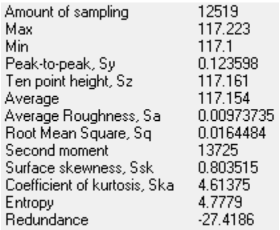
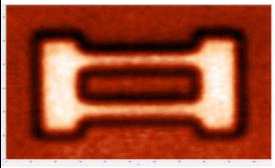
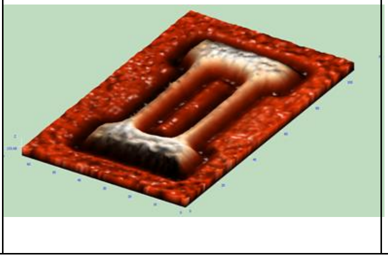
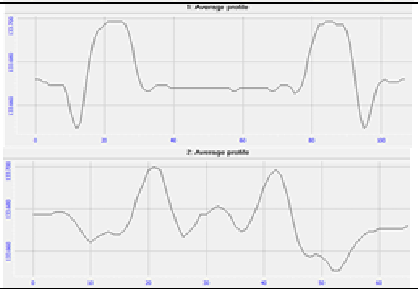
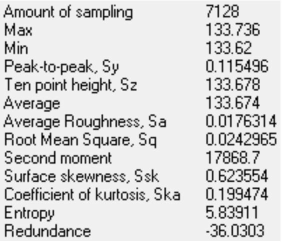
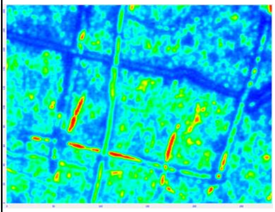
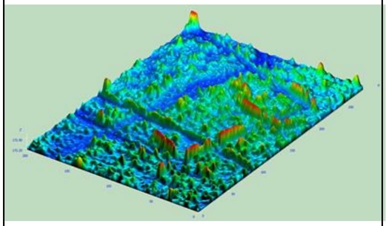
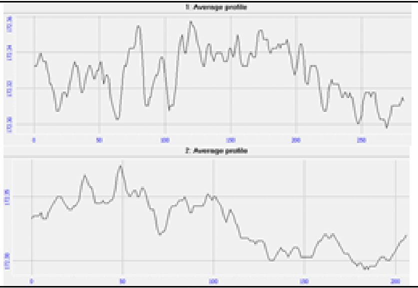
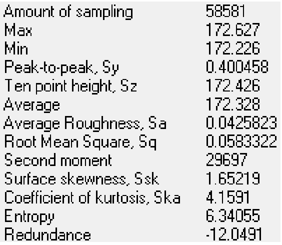
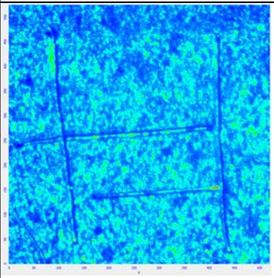
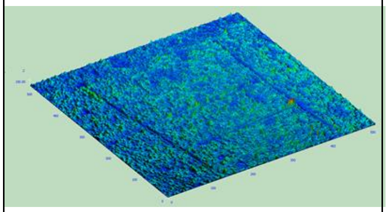
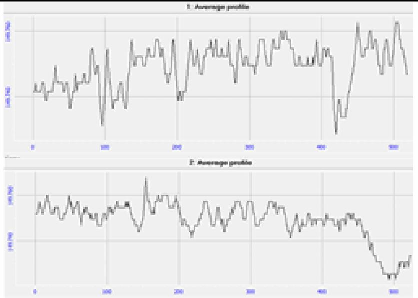
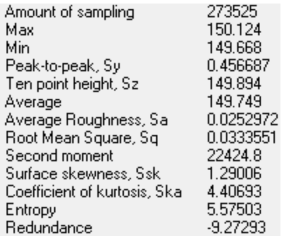
2D pattern	3D pattern	Average profile on the x/y axis	Tribological parameters (µm)
			Amount of sampling 18375 Max 141.353 Min 141.148 Peak-to-peak, Sy 0.205325 Ten point height, Sz 141.251 Average 141.258 Average Roughness, Sa 0.0225748 Root Mean Square, Sq 0.0340064 Second moment 19954 Surface skewness, Ssk -0.00789121 Coefficient of kurtosis, Ska 1.29181 Entropy 5.70821 Redundance -20.1868
			Amount of sampling 3010 Max 130.674 Min 130.602 Peak-to-peak, Sy 0.0726482 Ten point height, Sz 130.637 Average 130.647 Average Roughness, Sa 0.0134378 Root Mean Square, Sq 0.0159326 Second moment 17068.5 Surface skewness, Ssk -0.754565 Coefficient of kurtosis, Ska -0.436704 Entropy 5.6671 Redundance -55.0117
			Amount of sampling 12519 Max 117.223 Min 117.1 Peak-to-peak, Sy 0.123598 Ten point height, Sz 117.161 Average 117.154 Average Roughness, Sa 0.00973735 Root Mean Square, Sq 0.0164484 Second moment 13725 Surface skewness, Ssk 0.803515 Coefficient of kurtosis, Ska 4.61375 Entropy 4.7779 Redundance -27.4186
			Amount of sampling 7128 Max 133.736 Min 133.62 Peak-to-peak, Sy 0.115496 Ten point height, Sz 133.678 Average 133.674 Average Roughness, Sa 0.0176314 Root Mean Square, Sq 0.0242965 Second moment 17868.7 Surface skewness, Ssk 0.623554 Coefficient of kurtosis, Ska 0.199474 Entropy 5.83911 Redundance -36.0303

Table 3. AFM analysis of submicronic patterns produced by AFM lithography on Si substrate and thin Cu film.

2D pattern	3D pattern	Average profile on the x/y axis	Tribological parameters (µm)
Si substrate			Amount of sampling 58581 Max 172.627 Min 172.226 Peak-to-peak, Sy 0.400458 Ten point height, Sz 172.426 Average 172.328 Average Roughness, Sa 0.0425823 Root Mean Square, Sq 0.0583322 Second moment 29697 Surface skewness, Ssk 1.65219 Coefficient of kurtosis, Ska 4.1591 Entropy 6.34055 Redundance -12.0491
Thin Cu film			Amount of sampling 273525 Max 150.124 Min 149.668 Peak-to-peak, Sy 0.456687 Ten point height, Sz 149.894 Average 149.749 Average Roughness, Sa 0.0252972 Root Mean Square, Sq 0.0333551 Second moment 22424.8 Surface skewness, Ssk 1.29006 Coefficient of kurtosis, Ska 4.40693 Entropy 5.57503 Redundance -9.27293

Analysis of the 3D patterns and of the medium profiles on the two axes (x and y) demonstrate that electron beam lithography method allowed realization of the predefined shapes geometrically accurate on the substrates used.

The submicronic patterns realized using AFM force lithography were very simple compared to predefined ones, on both substrate types – Si and thin Cu layer.

Although AFM force lithography has advantages such as high precision, it is possible that in this case the contact force between the measuring head and the surface may not have been large enough to allow complete and powerful scratching of the substrate.

The authors consider that this is the main reason why AFM force lithography was not the proper technique to obtain complex submicronic patterns.

Electron beam lithography had another result because it is not a mechanical nature technique, and was not influenced by the mechanical risk factors that appeared during the experimentation.

Atomic force microscopy analysis and the determination of the tribological parameters (e.g. average roughness, surface skewness, coefficient of kurtosis, average profiles) offered information about the depth of the submicronic patterns obtained using the two lithography techniques.

The average depth values obtained for all types of submicronic patterns made are of the nanometer order, as follows:

- 130,746 nm depth for the patterns obtained on Si substrate by electron beam lithography;
- 96,044 nm depth for patterns obtained on Si substrate by AFM force lithography;
- 197,233 nm depth for patterns obtained on thin Cu film by electron beam lithography;
- 161,131 nm depth for patterns obtained on thin Cu film by AFM force lithography.

The depth of the patterns is higher for the thin Cu layer than for the Si substrate. One of the reasons why this depth difference appears, mainly in the case of AFM force lithography, could be the hardness of the two materials.

Taking into account the results obtained using AFM lithography, another reason could be that the measurement heads of the atomic force microscope used were not tough enough to implement a sufficient force for creating complex patterns.

Regarding the electron beam lithography, the authors consider that this technique is not influenced by risk factors as those that appear in the case of AFM lithography, thus achieving superior results when this technique is used.

4. CONCLUSIONS

The results obtained at the end of the project demonstrated that submicronic patterns can be realized on Si and Cu substrates using electron beam lithography and atomic force microscopy lithography.

Predefined complex geometric shapes of the patterns can be fully realized using electron beam lithography on the tested substrates.

Submicronic patterns simpler compared to those obtained by electron beam lithography were realized using atomic force microscopy lithography on both substrate types.

Thus, the main conclusion is that electron beam lithography allowed to obtain superior qualitative patterns compared to AFM lithography.

The authors consider that this difference appears due to the influence of some mechanical risk factors on the AFM force lithography.

These factors mainly refer to the substrates nature and this is the main reason why a great difference appears between the two lithography techniques.

Also, based on the atomic force microscopy analysis and the determination of the tribological parameters of the surfaces it was demonstrated that patterns with nano-scale depth were obtained using both types of lithography.

In the future, the submicronic patterns obtained will be used to design microsensors integrated in mechatronic and cyber-mixmechatronic systems and microsystems.

5. REFERENCES

1. Ioan Verdinas, Emil Cretu, *Elements of Nanotechnology*, Bucharest, (2007).
2. Sergey Edward Lyshevski, *Nano- and Micro-Electromechanical Systems: Fundamentals of Nano- and Microengineering*, 2nd edition, CRC Press (2005).
3. Ioan Stamatin, *Nanomaterials applications in biosensors, energy sources, medicine, biology. Elements of nanotechnology*, University of Bucharest, Romania (2008).
4. Mira Căldăraru, Florin Căldăraru, *Introduction to microelectronics*, university course, Cavallioti, (2009).
5. Miko Elwenspoek, R. Wiegerink, *Mechanical Microsensors*, 1st edition, Springer-Verlag Berlin Heidelberg, (2001).
6. A. Dumitriu, *Basics of mechatronic systems*, vol. 1, course, Transilvania University, Brasov, Romania, (2006).

7. Maluf Nadim, Williams Kirt, *An introduction to Microelectromechanical Systems Engineering,* 2nd edition, Artech House, Inc., US, (2004).
8. James J. Allen, *Microelectromechanical Systems Design*, CRC Press, Taylor & Francis Group, (2005).
9. Sergey Edward Lyshevski, *MEMS and NEMS – Systems, Devices and Structures,* 2nd edition, CRC Press, (2005).
10. Bharat Bhushan, *Springer Handbook of Nanotechnology*, 2rd edition, Springer Science Inc., 2007.
11. John Ernst Bjorkholm, EUV Lithography—The Successor to Optical Lithography?, *Intel Technololy Journal*. Vol. 2, pp. 1-8, (1998).
12. Wolwgang Menz, Jurgen Mohr, Oliver Paul, *Microsystem Technology,* Wiley-VCH Verlag GmbH, Germany, (2001).
13. Kenichi Takahata, *Micro Electronic and Mechanical Systems*, 1st edition, Intech, Croatia, (2009).
14. Kourosh Kalantar-zadeh, Benjamin Fry, *Nanotechnology-Enabled Sensors*, 1st edition, Springer, US, 2008