

Substrate Influence on the Mechanical and Tribological Characteristics of Gold Thin Films for MEMS Applications

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Abstract. The development of micro- and nano- electromechanical systems (MEMS/NEMS) makes use of different thin films such as aluminum, gold, silicon, silver, titanium nitride, silicon carbide etc. This study is a research concerning the influence of substrate nature on the tribological and mechanical characteristics of gold thin films elaborated by thermal evaporation method, for space applications. Three different substrates were employed, namely: C45 steel, plastic (polycarbonate) and glass. Atomic force microscopy investigations were performed in order to characterize the obtained thin films at nanoscale. The nanohardness, Young's modulus, roughness and the friction force are some characteristics that were determined. A significant influence of substrate nature on both mechanical and tribological properties of researched gold thin films was marked out. Regarding the topography, the smallest roughness was determined on the gold thin films deposited on glass substrate.

Introduction

Nowadays, researcher's attention is focused on the development of miniaturized devices (micro- and nano- electromechanical systems) for applications in all domains (automotive, biomedical, electronics, space industries etc.). A wide range of materials used as bulk materials or thin films are employed for manufacturing such devices [1-7]. Gold as well as aluminum and silver is often used for elaborating devices for MEMS applications. The results of the researchers relating to gold thin films deposited by different chemical or physical methods are exploited in a large number of scientific articles [8-14].

The failure mechanisms in MEMS switches are adhesion, stiction and wear of ohmic contact phenomena. The ideal contact in this type of switches should be very conductive and flat. Gold is widely used in MEMS applications due to its high conductivity and chemical inertness. In spite that we need to improve the hardness of this metal by incorporating different particles such as copper, nickel, silver, palladium platinum etc. [8]. Its high electrical conductivity, optical reflectivity as well as its low Young's modulus (79 GPa) make gold suitable for manufacturing micro- devices for MEMS applications [14].

Physical vapor deposition, plasma-assisted chemical vapor deposition, laser ablation, RF reactive sputtering, reactive evaporation, ion-beam deposition and so forth are some techniques employed for fabricating thin films for MEMS devices.

The goal of this paper is to elaborate and characterize gold thin films by thermal evaporation method on different substrates in order to emphasize its influence on the mechanical and tribological properties.

Materials and methods

Materials

Gold thin films were deposited on three different materials in order to highlight substrate influence on the mechanical and tribological characteristics of the elaborated samples. The materials employed for substrates were C45 steel, plastic (polycarbonate) and glass respectively. Gold target with the purity of 99.99 % was employed. The process of elaboration of the samples was performed in a chamber under vacuum protection.

Methods

Gold thin films were elaborated by the thermal evaporation method. First, the three kinds of substrates were prepared. Cylindrical samples, 15 mm in diameter, made of C45 steel were first cut and then rectified and polished with flints of granulation up to 1200. The plastic and glass substrates were cut in square shape having the dimensions of 25x25 mm. Further, the three types of substrates were cleaned in an ultrasonic bath for removing any possible remaining impurities using high purity alcohol (99.9 %). The samples were then dried with hot air. The so-obtained substrates were then introduced in the chamber under vacuum protection where the deposition of gold thin films was realized. The thermal evaporation process was done under vacuum atmosphere ($5 \cdot 10^{-6}$ torr). The substrates were not preheated before gold deposition. The melting and the evaporation of the gold were realized by using resistance heated tungsten sources ("boat" type). The resistors were charged to a current of 60-80 A so that the process can take place. The distance between the resistors and the substrates was 50 mm. The thickness of the obtained gold thin films was determined to be about 70 nm. The following notation was settled for the obtained samples in order to facilitate the interpretation of the results: "Au_substrate nature" (example: "Au_glass" represents the gold thin films samples deposited on glass substrate).

The so-obtained samples were characterized from the mechanical and tribological point of view at nanoscale. The nanocharacterization of the researched samples was performed in a clean environment using a XE 70 atomic force microscope. The determination of the tribological characteristic (friction force) and the surface parameter (roughness) for the researched thin films was realized using a PPP-CONTSCR-10M cantilever. The tip of this cantilever is made of silicon. Its radius and height are 8 nm and 12.5 μm respectively. The tests were effectuated for a relative humidity of about 50 % at room temperature (22 °C). The scanning frequency was 0.75 Hz. According to the data given by the producer, the dimensions of the cantilever used for investigations are:

- thickness: $h = 1 \mu\text{m}$;
- width: $b = 48 \mu\text{m}$;
- length: $l = 225 \mu\text{m}$.

The mechanical characteristics (Young's modulus and nanohardness) of the studied materials were determined by nanoindentation tests which employed a TD21562 nanoindenter (sapphire cantilever with diamond tip). The characteristics of the nanoindenter given by the manufacturer are:

- cantilever stiffness: 144 N/m;
- cantilever length: 782 μm ;
- tip thickness: 24 μm ;
- tip height: 109 μm ;
- tip radius: 25 nm;
- inclination: 12 °;
- front, half and side angles: 90, 30 and 79 °.

The tests were carried out at two different forces limit namely 50 nN and 100 nN respectively. The XEI Image Processing Tool for SPM data used the Oliver and Pharr method for the interpretation of the images obtained with the XEP Data Acquisition Program for the determination of the mechanical properties.

Theoretical formula

The determination of friction force was one of the aims of the researchers in order to characterize the obtained thin films from the tribological point of view at a nanoscale. Friction force can be calculated based on the data provided by the employed atomic force microscope using the following formula [15]:

$$F_f = \frac{d_z \cdot r \cdot G \cdot h^3 \cdot b}{l^2 \cdot s} \quad (1)$$

where d_z represents tip rotational deflection, r is a constant ($r = 0.33$), G is shear modulus (for silicon: $G = 53.9 \cdot 10^{-3} \text{ N}/\mu\text{m}^2$), h , b and l are the dimensions of the cantilever, while s is tip height ($s = 12.5 \mu\text{m}$).

The values of tip rotational deflection are taken from the data offered by the program used for interpreting the images acquired with XEP Data Acquisition Program (XEI Image Processing Tool for SPM data).

Results and discussions

The research aimed at determining the mechanical and tribological properties of gold thin films elaborated by thermal evaporation method by atomic force microscopy investigations. Tests were performed in order to analyze the topography of the obtained samples measuring their roughness at the same time. Nanohardness and Young's modulus are the mechanical characteristics that were determined, while the friction force between the tip and sample surface is the tribological property of interest.

Topography

3D images of the obtained gold thin films were achieved using the XEI Image Processing Tool for SPM data (Fig. 1). The gold thin films deposited on glass substrates presents the smoothest surface from all three kind of samples while the gold thin films deposited on plastic substrates showed the roughest surface. The roughness of the researched samples was determined in order to sustain the previous statement.

An important influence of the substrate on this parameter was marked out. The values determined for surface parameter are given in Table 1. The average roughness ranged between about 3 nm for the samples deposited on glass substrate and about 30 nm for the samples deposited on plastic surface. The roughness of gold thin films elaborated on glass is approximately 3.5 and 8.5 times smaller than the roughness of the gold thin films elaborated on steel and plastic substrates respectively. A possible explanation might be the topography of the substrate which has a significant influence on the topography of the gold thin films. The preparation of the substrates has also an important impact on the surface parameter - plastic surfaces are the most difficult to process from the three material used for substrates.

Table 1. Roughness (R_a) of the researched samples

Material	Gold_glass	Gold_plastic	Gold_steel
Roughness, R_a (nm)	3.553	30.187	11.943

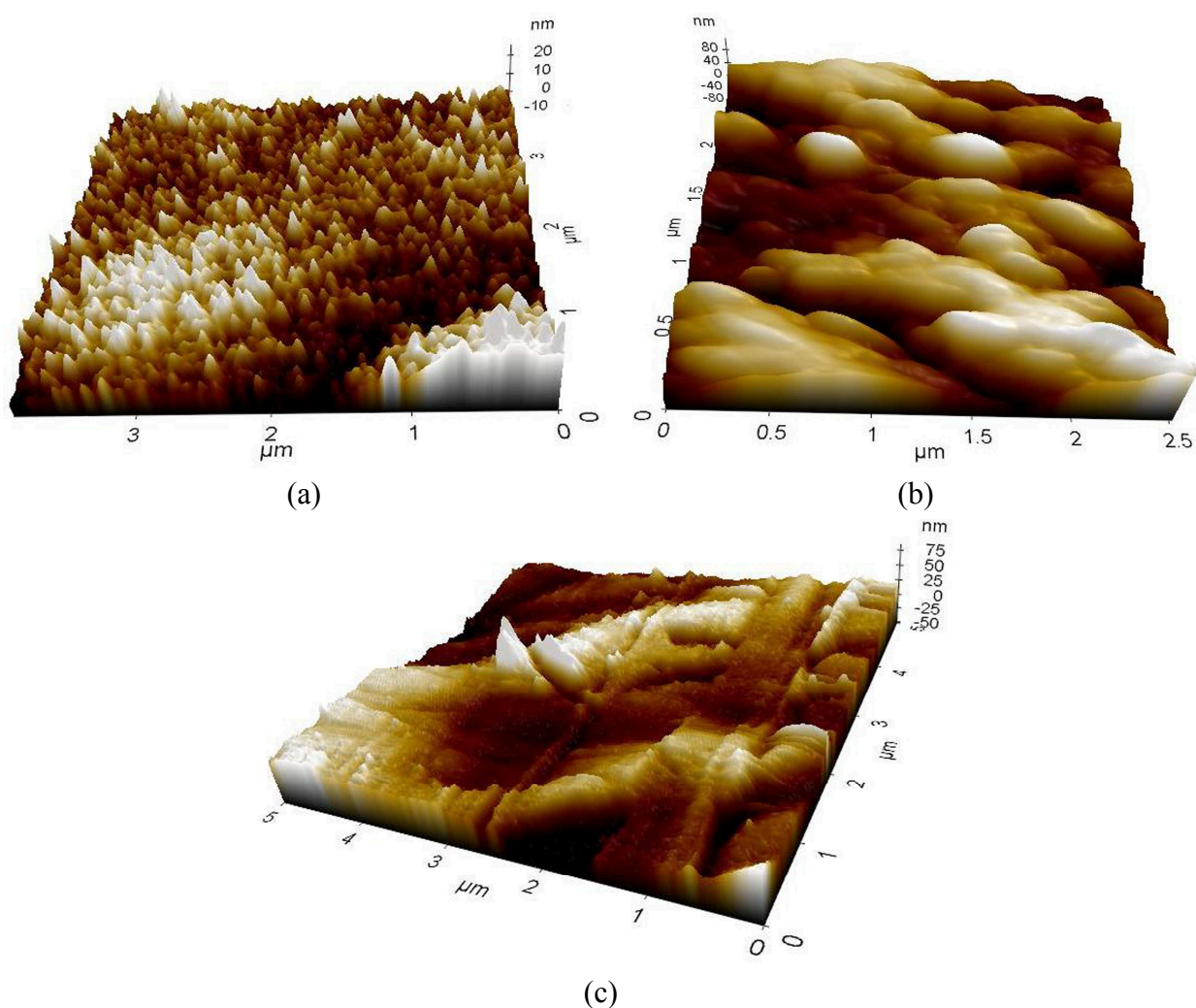


Fig. 1. 3D images of gold thin films deposited on (a) glass, (b) plastic and (c) steel substrates respectively

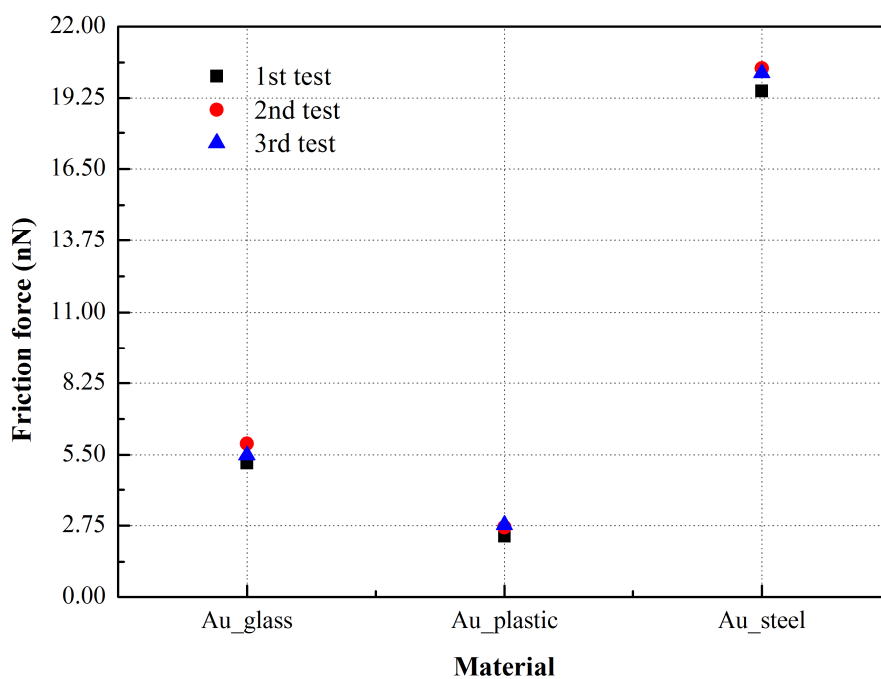


Fig. 2. Friction force between AFM tip and gold thin films deposited on glass, plastic and steel respectively

The fluctuation of the friction force between the AFM tip and the surfaces for the three types of samples is graphically given in Fig. 2. The smallest and the closest values for the friction parameter were determined on the gold thin film elaborated on plastic substrates. Instead the values of the friction force for the samples deposited on glass and steel substrates were approximately two and eight times higher respectively than the friction force of the samples deposited on plastic substrates. The variation of the friction force may be due to the fact that each sample presents a different surface energy.

The determination of both mechanical characteristics (nanohardness and Young's modulus) was realized using the Oliver and Pharr method for the interpretation of the force-Z scan curves achieved with the XEP Data Acquisition Program. Fig. 3 presents a force-Z scan curve characteristic to a gold thin film deposited on glass substrate.

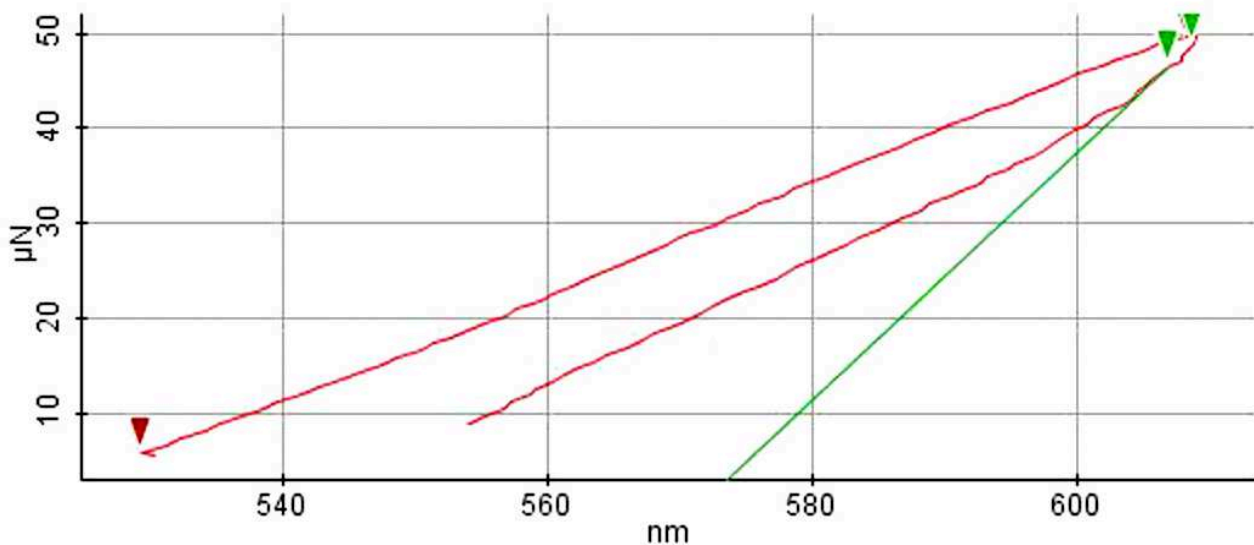


Fig. 3. Force-Z scan curve of a gold thin film deposited on glass substrate for determining the mechanical characteristics

Nanohardness of the researched thin films obtained by thermal evaporation when testing with two forces limit (50 and 100 nN respectively) is graphically given in Fig. 4. A significant impact on this mechanical characteristic of substrate nature was highlighted. As expected, the values of this parameter when the samples were tested with 50 nN are higher than the values for the samples tested with 100 nN. The increase of the force limit leads to the decrease of the nanohardness for the samples elaborated on the same substrate. The gold thin films deposited on steel substrate presented the highest values of the nanohardness when force limit was 50 nN, while the gold thin films deposited on glass substrate showed the highest values of this parameter when force limit was 100 nN. If the nanohardness of the samples elaborated on steel substrates is approximately 16 % higher than that of the samples deposited on glass substrates, the nanohardness of the samples elaborated on plastic substrates is about 50 % smaller than that of the samples deposited on steel and glass substrates.

Concerning the Young's modulus of the studied gold thin films, the results marked out a significant influence of substrate nature on this characteristic. The values of Young's modulus for the three kinds of samples tested with 50 and 100 nN are graphically given in Fig. 5. As the nanohardness of researched samples, the values of Young's modulus decreases when the force limit increases. The highest value of this parameter was determined for the gold thin films deposited on glass substrate when the force limit was 50 nN, while the smallest value of Young's modulus was determined for the samples elaborated on plastic substrates when the force limit was 100 nN.

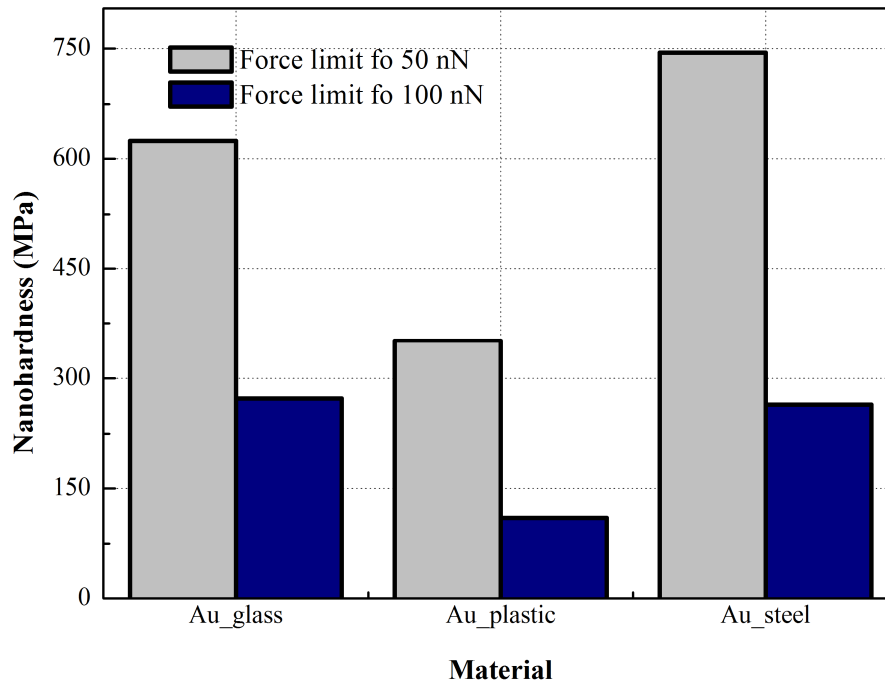


Fig. 4. Nanohardness of gold thin films deposited on glass, plastic and steel substrates

When the tests were performed with a force limit of 50 nN, the Young's modulus of gold thin films deposited on glass substrates is approximately 5 and 30 % higher than the Young's modulus of the samples elaborated on steel and plastic substrates respectively. Instead when a force limit of 100 nN was employed, the Young's modulus of gold thin films deposited on steel substrates is about 13 and 26 % higher than the Young's modulus of the samples deposited on glass and plastic substrates respectively.

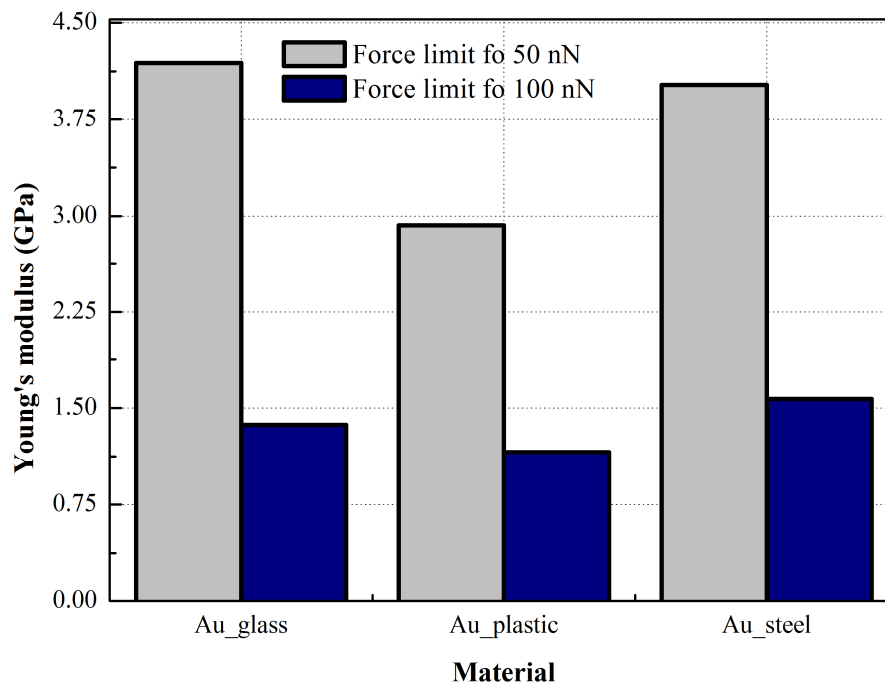


Fig. 5. Young's modulus of gold thin films deposited on glass, plastic and steel substrates

The explanation for the fluctuation of both mechanical characteristics might be the surface energies that differ for each sample. The chemical bonds that appear between the gold thin films and the substrate material (glass, steel, and plastic respectively) have different intensities that lead to different surface energies.

Figure 6 present images of the gold thin films deposited on steel substrate after the nanoindentation tests. The traces left on the sample by the nanoindenter when testing with 50 and 100 nN are marked out on the 3D image. The results also aimed at determining the depth of the traces. The value measured for the depth of the trace obtained when a force limit of 100 nN was employed is about three times higher than the value of the depth for the trace obtained when the force limit was 50 nN.

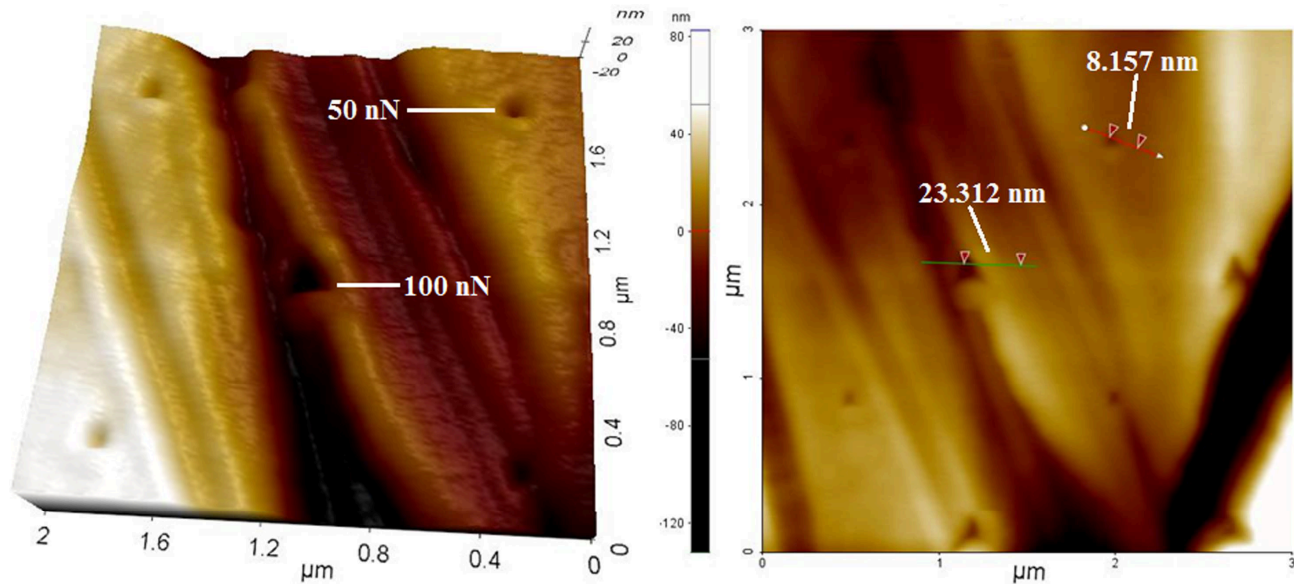


Fig. 6. Images of the traces left on the gold thin film deposited on steel substrate after the nanoindentation tests

Note: The depth of the traces when testing with 50 and 100 nN is 8.157 nm and 23.213 nm respectively

Conclusions

A significant influence of substrate nature on the mechanical and tribological characteristics of gold thin films deposited by thermal evaporation was marked out. Three different substrates were employed in order to achieve this purpose, namely glass, plastic and steel. The topography of the elaborated gold thin films is strongly influence by the topography of the substrate and by substrate preparation. The gold thin films deposited on glass substrate are characterized by the smallest value of the roughness and implicitly by the smoothest surface. Regarding the tribological behavior, the highest value for the friction force between the AFM tip and the sample surface were determined for the gold thin films deposited on steel substrates. The nanoindentation tests showed a considerable change of both nanohardness and Young's modulus when different forces limit and different substrates were used. The increase of the force limit led to the decrease of the mechanical characteristics. The highest value of nanohardness was determined on the gold thin films deposited on steel substrate when testing with a force limit of 50 nN, while the highest value of Young's modulus was achieved on the gold thin films elaborated on glass substrate when a force limit of 50 nN was employed.

Acknowledgments

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