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Aluminium doped silver mirrors: magnetron sputtering deposition and investigation

Final Work of Master studies

Study programme Laser Technology

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Introduction

Silver is very widely used in many advanced technology industries. In space industry high performance silver mirrors are in high increasing demand. High reflectance and thermal resistance from -80 $°C$ to +35 $°C$ Ag mirrors were used in the Kepler Space Telescope mission. With the reflectance of ≈ 95 % highly protected mirrors were created to cover a spectral region from 400 *nm* to IR. Structure of protective layers of $Ni\text{-}CrN_x + Ag + Ni\text{-}CrN_x + Si_3N_4$ was used and performed very well in tests [1].

A protective coating is very often used in combination with silver, as it enhances Ag tarnish resistance capabilities. Due to its optical performance Ag exists in many optical devices, sensors, electronics, and other application fields [2]. This metal is irreplaceable considering its optical performance and cost-effectiveness [3]. The downside is that silver tends to react with the atmosphere and tarnish, which leads to decreased reflectivity and damaged material. In many cases, this problem is partly solved by using protective layers, for example, SiO_2 layer is often used to prolong Ag mirrors lifetime. By being cost-effective metal with irreplaceable optical properties, Ag is researched in other ways rather than just choosing the right protective layer [4, 5].

Hybrid layers of aluminium doped silver mirrors are being researched. Such combination of metals is very attractive in the way of increased tarnish resistance and enhanced optical and physical characteristics [5]. Nevertheless, the Al doping rate must be monitored because higher dopant levels may cause decrease in film reflectance [6]. Modern mirrors must comply with the standards of film parameters such as uniformity, resistance, performance, and longevity. In this work we investigated Al doped Ag mirrors deposited using one of the most popular and precise thin film deposition techniques called Magnetron Sputtering (MS).

Aim

The aim of this work is to investigate the optimum aluminium doping of silver mirrors in terms of best resistance, highest reflectance, and smallest surface roughness.

Tasks

1) Prepare silver mirrors with various aluminium doping concentrations;

2) Investigate roughness and reflectance changes of the silver mirror with various aluminium doping;

3) Investigate the radiation damage threshold of deposited samples in order to use them in space applications.

1. Literature overview

1.1 Sputtering

Sputtering is one of the oldest and the most common energetics processes of material deposition. The main components of the sputtering system are a vacuum chamber with anode and cathode. A pressure of around 1 Pa and a voltage of a few kV are used. The working principle of this method uses positive ions from the discharge in gas which are attracted to negatively charged cathode with a target which is used as a deposition material. The kinetic energy of positive ions colliding with the target is enough to sputter target atoms into the vacuum chamber, hopefully in a straight line so they condense on the substrate which is located above the target [7].

1.1.1 Magnetron sputtering

Nowadays, one of the most popular thin film deposition methods is called magnetron sputtering. Magnetron sputtering is commonly used due to its advantages compared with other coating techniques. The main advantages are high-purity films, ability to coat heat-sensitive substrates, extremely high adhesion of films, high deposition rates, ease of sputtering any metal, alloy or compound, excellent coverage of steps and small features and ease of method automation [8].

The key element of magnetron sputtering is the generation of the plasma region above the cathode. The main derivatives of this effect are working gas atoms and electrons which are accelerated in the electric field between cathode and anode. The appearance of plasma ensures that electrons emitted from the cathode have sufficient energy to ionize working gas molecules. As soon as we have all the main players of discussed method: positive ions and cathode with a target, the sputtering process can begin (Fig.1).

Vital role in magnetron sputtering method efficiency is played by magnetrons. Penning trap principle is used to trap primary electrons emitted from cathode and secondary electrons that are generated after the bombardment of the target by positive ions (Fig. 2). The localized electron region close to the target is called the 'racetrack' here electrons are more likely to ionize the working gas atoms. This method of electron trapping lets the magnetron sputtering system work at lower voltages and higher sputtering efficiency [8, 9].
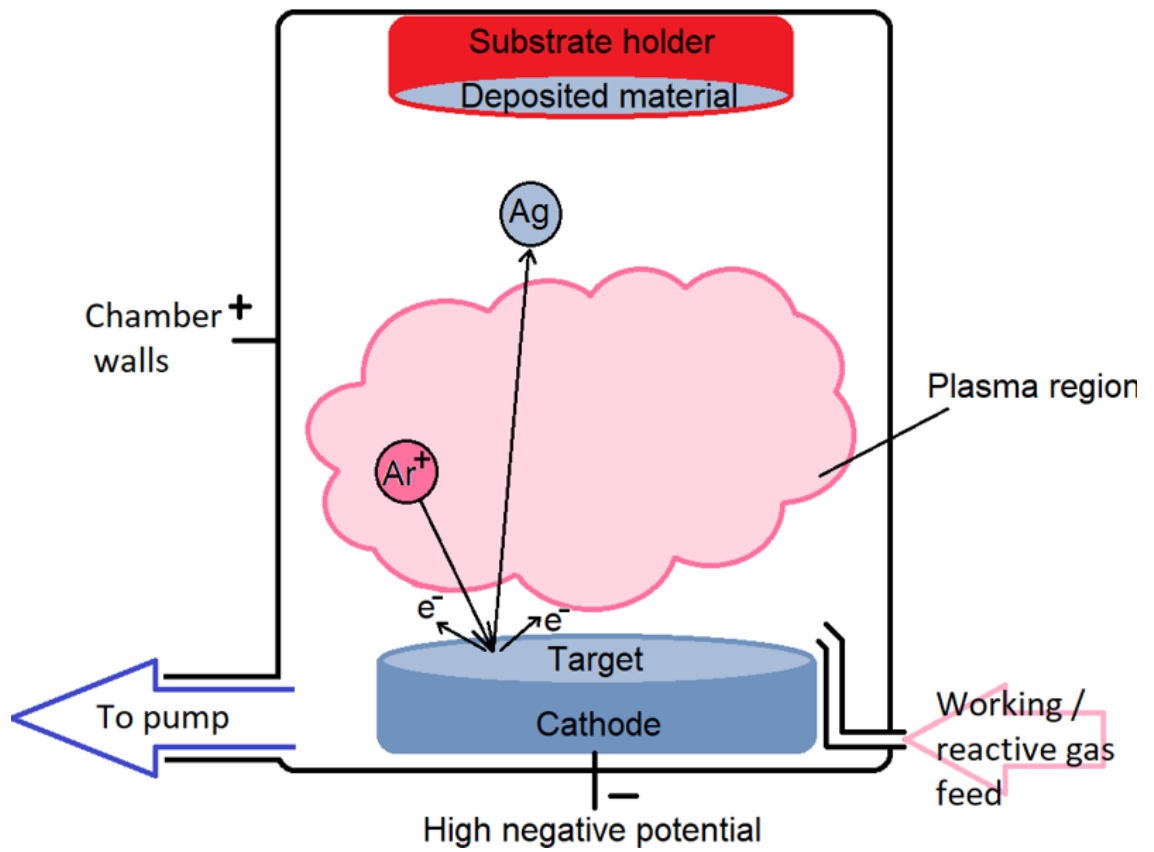
Fig. 1 Principle scheme of magnetron sputtering method with argon as a working gas and silver as a target material.
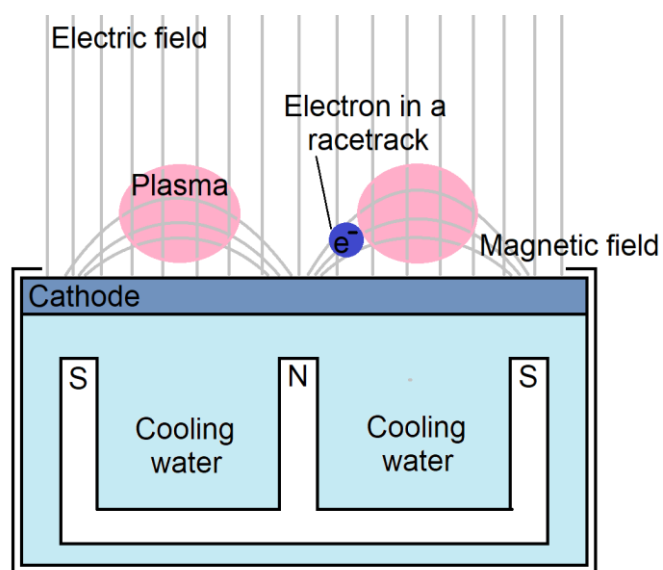
Fig. 2 Schematic cross-section of a magnetron cathode. Adapted from [7].

1.2 Silver mirrors application

Compared to other metals for coating applications, silver is the most commonly used. It might be found in nearly every field of industry. Such tendencies were influenced by the fact that silver is often considered a low-cost substitute for other metals like gold and palladium. Nevertheless, silver provides high-performance properties in tensile strength, heat absorption, corrosion resistance, and conductivity. Surely, the primary benefit that is characteristic of silver and is widely used in optical mirror applications is high reflectivity and low emissivity that is crucial for infrared applications (Fig.3) [5]. The reflectance of a metal mirror can be calculated from the index of refraction n and the extinction coefficient k. By using these parameters (Table 1) and equation (1) the reflectance of silver in the air can be calculated [3].

$$R(\%) = \frac{(n-1)^2+k^2}{(n+1)^2+k^2} \times 100 \qquad (1)$$

Table 1. n and k values for silver [3].

Wavelength (μm)	0.2	0.3	0.4	0.5	0.6	0.7	1	2	4	10
n	1.07	1.51	0.17	0.13	0.12	0.14	0.21	0.65	2.3	13.3
k	1.24	0.96	1.95	2.92	3.73	4.52	6.76	12.2	24.3	54
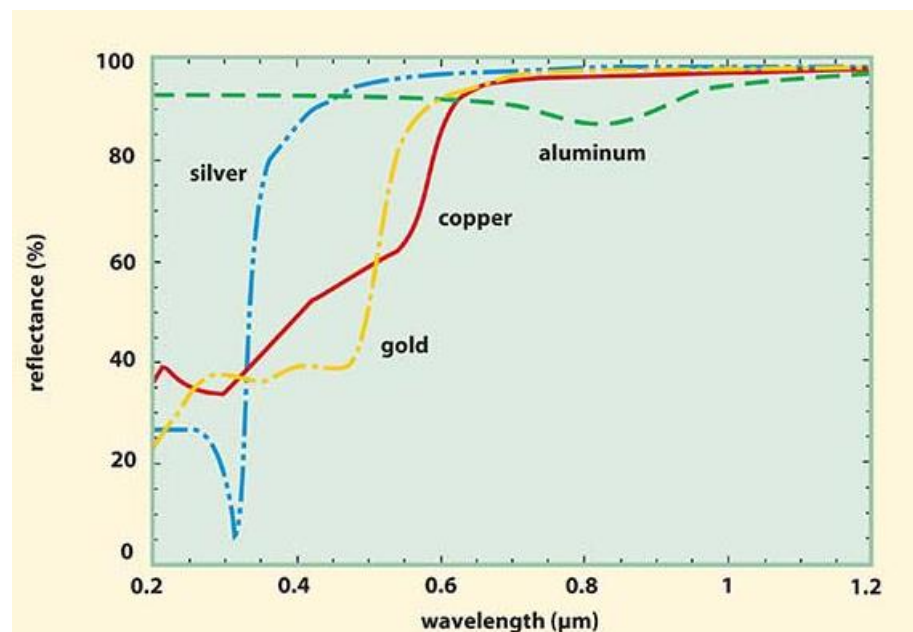
Fig. 3. The reflectance of several shiny metals [3].

Silver has a high reflectance in the visible and infrared spectral regions. It is an excellent choice for broadband applications, but this metal has a few drawbacks. Bare silver is considered not practical due to its property to tarnish and doubtful adhesion to surfaces like glass. To minimize these drawbacks, a protective coating of a dielectric layers or adhesion layer of other metals can be used. To minimize losses in the UV region a combination of silver and aluminium hybrid coatings is being widely explored [5, 10].

Silver films are used in many technological applications, for example, in solar devices, optical devices, sensors, electronics, and plasmonic devices. Such widespread of Ag films is due to their optical, electrical, mechanical, catalytic, and antibacterial properties [2]. One of the most prominent applications of protected silver mirrors are telescopes and aerospace industries. Use of silver increases the telescopes' sensitivity, reflectance and achieves significant infrared optimization while being cost-effective. Acknowledging silver properties new space missions consider this metal as their primary choice. As an example, for The Kepler Mission researchers designed an enhanced silver coating for the best performance that could be achieved [5].

## 1.2.1 Challenges encountered by mirrors in space application

It is easier and cheaper to test manufactured mirrors and other coatings in earth laboratories, than in space missions. The basic technology that is used for testing coatings when imitating a space environment is the irradiation durability test. Mostly, accelerated helium ions are used. The damage done to the surface of the film is monitored. Nevertheless, there are many more things that can influence the degradation of optical components in space.

As it is reported in Ref. [11] the main optical components concern used in low earth orbits at altitudes up to 700 *km* is atomic oxygen (AO). It is a free radical with a large potential to harm optical components and to act as a participant for contamination. AO is mostly harmful in low earth orbit above 100 *km* where it is created by solar UV radiation. Many bare metal surfaces and coatings are susceptive to AO while most oxide-based materials can resist it pretty well. Thermal processes influence thin film performance in space missions. Usually, optics need to withstand at least five hours at -62 *ºC* and five hours at 71 *ºC*. Strong thermal variations induce mechanical stress that may modify optical components' structure or layer adhesion level. In many cases to fight thermal processes tests before space missions are made and also protective coatings are used. A more challenging thing to handle in space is UV radiation. In many cases, UV radiation promotes composition change in materials, which often leads to unwanted absorption. Because of that UV radiation must be considered and qualification tests are done. An additional problem related to radiation is accompanied by charged particles. Cosmic rays are a continuous flow of charged particles 85 *%* protons, 14 *%* helium, and the residual 1 *%* heavy ions. For example, normal solar activity may produce protons of ≈1 *keV* and for more energetic activities particles of *MeV* can be detected on Earth's surface. Particles with energies in the keV range will implant within the coating and depending on their density will induce optical, structural, and morphological changes. High-energy particles penetrate through the coating of 10 *µm* and impact the substrate. Usually charged particles influence optical change in the UV region and their damage can be minimized using various protective coatings [11].

1.2.2 Silver mirrors preparation

Magnetron sputtering deposition method is widely used for depositing various metallic films. This deposition technique is also well suited for depositing Ag films due to its capability to control deposition parameters. By manipulating sputtering parameters, the magnitude of stress which is induced on Ag thin film can be reduced. This property of MS deposition method is important when producing high quality Ag thin films, because due to over highly energetic particles hitting Ag film certain structural deformations can occur thus will worsen the performance of the thin film [12].

As it is reported in Ref. [13] before the sputtering process, the substrates are prepared by cleaning them with ethanol or better by using an ultrasonic washer. Geometrical parameters target-to-substrate distance, magnetron head tilt, and others are adjusted. For 25 - 350 *nm* thick Ag thin films presputtering of chromium-based coating is done to reduce run-in wear and to improve tribological properties. It is possible to use both d.c. and r.f. deposition methods but it was investigated that r.f. sputtering mode is more suitable for Ag thin films due to accurate and controllable thickness achievability. The main difference between d.c. and r.f. modes are film deposition rate. For both of these sputtering modes, the deposition rate of the film increases linearly as the sputtering power increases (Fig. 4). Analysing for similar sputtering power between 400 *W* and 500 *W* deposition rate for d.c. was twice as much than operating in r.f. mode. Operating voltage also differs by a factor of two, d.c. target voltage was 400 *V* and the r.f. target voltage was 200 *V*. For that reason, target voltage appears as the dominant factor affecting the deposition rate of Ag films. As a result, operating at lower voltages r.f. sputtering mode can be more easily controllable. Moreover, fully dense structures of Ag films are prepared by r.f. sputtering mode. This is possible due to the atomic peening mechanism - when surface Ag atoms, after bombardment by relatively high-energy particles, can move to deeper positions in the growing film [13].
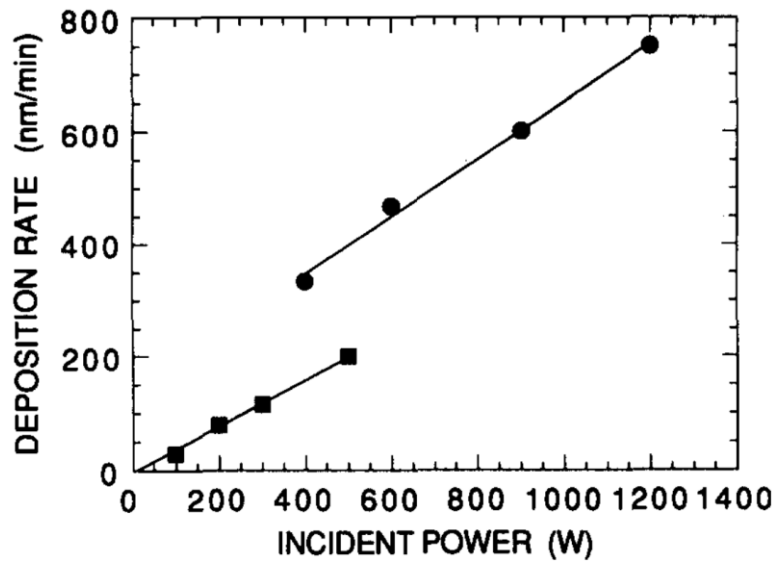
Fig. 4. Deposition rate of silver films *vs.* incident power:
●, d.c. sputtering mode; ■, r.f. sputtering mode [13].

As it is reported in Ref. [14] for nanostructured Ag, sputtering parameters that play a key role when depositing Ag thin films are sputtering time, power and sputtering gas. When analysing formed nanostructures of deposited Ag thin films, it is notable that grain size gradually enlarges when increasing sputtering power. The same tendencies prevail when increasing the time of the deposition process so in many cases when managing these two parameters desired grain size and film thickness are achieved. If it is needed to influence Ag thin films nanostructures even more it is possible to use different sputtering gasses. Usually, argon is used in MS and it allows to form grain like Ag nanostructures. When using nitrogen as a sputtering gas different result occurs - flat spherical structures of nano-particles are formed. Using different sputtering gases not only allows to moderate Ag thin film nanostructures but also the contamination of oxygen and carbon varies from the gas that is used. For argon ion sputtering, the content of oxygen and carbon is less than 6.9 % and 4.5 %, and for N_2, less than 4.7 % and 3.6 % [14].

1.2.3 Investigations on various films that were used for protection of silver mirrors (SiO_2, $SiON$, Al_2O_3, TiO_2)

Noble metals such as silver has attracted considerable interest in fields of scientific applications. Silver mirror coatings are of crucial importance in many optical applications and they are essential components for optical systems or devices where reflective surfaces are required. Ag on its own is ideal for observing a wide range of light wavelengths. For infrared applications, it is especially useful due to low emissivity and high reflectivity [4]. In many cases, Ag is used in combination with other materials in order to enhance films performance or manipulate some parameters. However pure Ag thin films without protective layer have a low environmental stability. For this reason, silver thin films need a protection and in most cases layers of TiO_2, SiO_2, Al_2O_3, Si_3N_4 are used [15, 16].

The combination of titanium dioxide and silver is quite widely used for its optical, mechanical, photocatalytic, and biocidical properties. Ag/Ti films are beneficial for their tribological properties such as reduced sliding friction and wear. Due to that Ag/Ti films are suitable to provide lubrication and might be used for advanced applications such as engine seals, bearings, and other sliding components [17, 18]. It is well known that Ag is used for solar reflectors but unfortunately, without a protection layer this material is easily corroded after a long-time exposition to the environment. High transmittance materials like glass or polymethylmethacrylate are used for Ag protection, but such bulk materials exhibit different physical properties rather than thin films. For the protection of Ag layer, SiO_2 and TiO_2 are used (Fig. 5), this combination maintains high reflectivity and assures good aging resistance. Moreover, titanium dioxide provides hydrophilicity and photocatalytic properties so by using such a combination of thin films protection layers it is possible to create a self-cleaning mirror that maintains high reflectivity of Ag for a much longer time [19]. Combining titanium dioxide and silver leads not only to self-cleaning film, but the direct toxicity of Ag also kills *Escherichia coli* bacteria with 100 % efficiency.
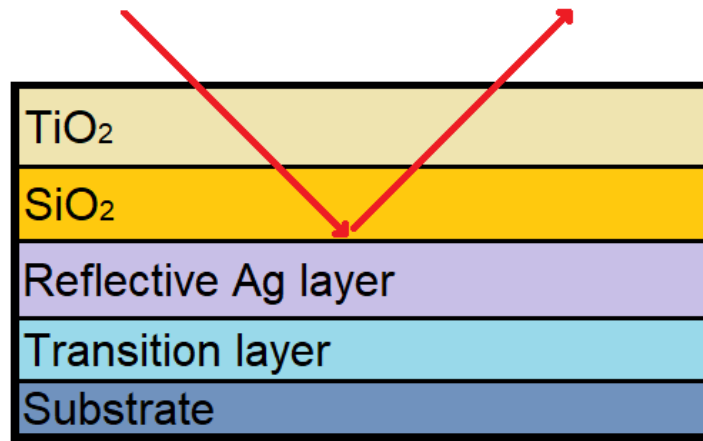
Fig. 5. The architecture of self-cleaning mirror with high reflectivity.

Overall Ti/Ag films may not only provide self-cleaning but also self-disinfection due to biocidical effect which also can be improved by UV-induced photocatalytic activity [17].

For ground- and space-based applications silver thin films require protective coatings that offer high resistance to aqueous solutions, acid, and do not create high mechanical stress. As a consequence of Ag film layer degradation compounds such as Ag_2S, $AgCl$ or Ag_2O are formed. These compounds rapidly decrease the reflectivity of Ag, for this reason, multiple protection layers are used with a final layer which offers the highest resistance. Protective layers such as Si_3N_4 , SiO_2, and Al_2O_3 can offer resistance to most aqueous solutions. Si_3N_4 can offer the highest resistance to the acid of the mentioned layers and due to low induced mechanical stress Si_3N_4 is often used as a final layer. SiO_2 and Al_2O_3 also performs quite well against most acids, but not when exposed to a basic solutions in some cases at pH value of 10 Al_2O_3 may start to dissolve. The interaction with OH ions creates mechanical stress in such protective layers and can lead to cracks. Overall, as a protective layer for Ag thin films Si_3N_4 is more stable than SiO_2 and SiO_2 is more stable than Al_2O_3 [16]. Although protective layers are better to protect edges of the sample and can work pretty well at pH 7 [20].

1.2.4 Investigation on various properties of mixing silver and aluminium

Metallic alloys have a huge potential for plasmonic materials applications due to large electron densities and they are very widely used as reflective coatings. Due to the similarity of Ag and Al atomic radius, there is almost no change in silver lattice parameters. However, when Al concentration exceeds 2-3 % unwanted effects may occur. The addition of Al to the Ag-Al system causes an increase in the electron-to-atom ratio which then leads to a red-shift in reflectance spectra (Fig. 6). Although when Al concentration is as high as 6 % other interesting processes may take place. At such and higher Al concentrations the oxidation process of external Al may occur. As a result of oxidation protective layer is formed, however, this protection comes with reflectance loses at around ≈ 600 *nm* wavelength [21, 6].
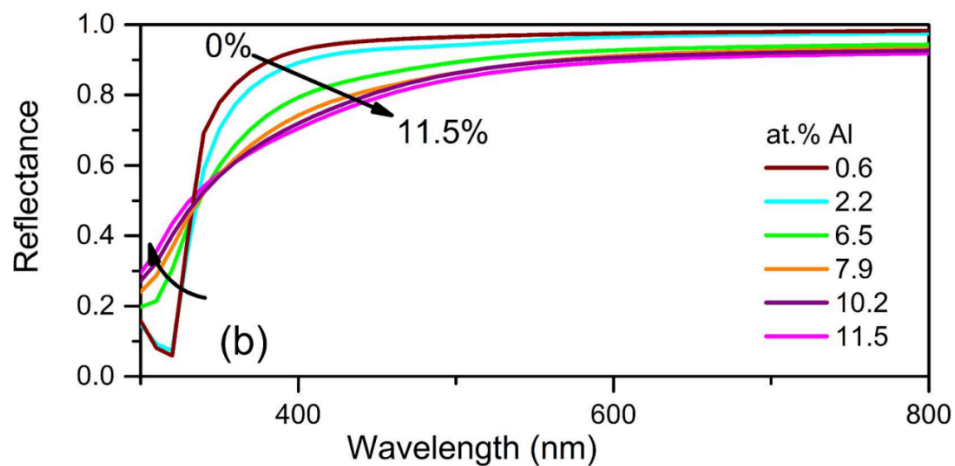
**Fig. 6.** Reflectance of Ag with different concentrations of Al [6].

It is known, that the most critical phenomenon of pure Ag thin films is corrosion because of tarnishing in the atmosphere. This problem causes degradation and limits application of the film. The corrosion degradation is usually connected with a decrease in reflectivity.

In comparison to Ag, Al changes little on the atmospheric exposure. Nevertheless, the Al reflectance is not as high as that of Ag in the range from 400 *nm* to IR. Also, the roughness and protection of the surface of the thin film can be improved [22]. This combination of Ag/Al performs best at reflectivity when Al concentrations are low, and other optical parameters can be varied when the ratio of these two components are changed [21, 22].

2. Experimental details

Kurt J. Lesker Company magnetron sputtering system was used for the preparation of all investigated samples.

It was used double-sided polished fused silica substrates of 25.4 *mm* diameter and 1 *mm* thickness.
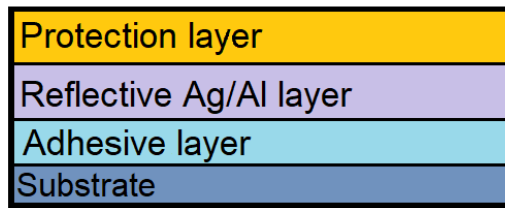
Fig. 7. Experimental scheme of the samples.

Ag/Al layer thickness for all samples was – 150 *nm*. Two magnetrons of Ag and Al (or one in case of pure Ag) were working at the same time to form uniform film.

The system was initially pumped down with a scroll pump (XDS 35i from Edwards; 11 *L/s* air) and after with a cryogenic pump (Cryo-Torr 8F series from Helix Technology Corporation; 1500 *L/s* air) to a base pressure below 5×10^{-7} *Torr*. All process gases used for deposition were >99.999 *%* pure. The Ar flow rate was 20 *sccm* and the pumping speed of the cryogenic pump was adjusted to attain the argon pressure at the same value of 2.2 *mTorr*. The settings of the Ar flow rate and the pumping speed were not changed during the processes. Prior to depositing films, the target was pre-sputtered for 5 *min* in Ar to remove any surface oxides.

100 % Ag – **Sample 1**:
- Ag sputtering power – 200 *W*.

95 % Ag + 5 % Al – **Sample 2**:
- Ag sputtering power – 200 *W*;
- Al sputtering power – 20 *W*.

92 % Ag + 8 % Al – **Sample 3**:
- Ag sputtering power – 200 *W*;
- Al sputtering power – 30 *W*.

90 % Ag + 10 % Al – **Sample 4**:
- Ag sputtering power – 200 *W*;
- Al sputtering power – 40 *W*.

85 % Ag + 15 % Al – **Sample 5**:
- Ag sputtering power – 200 *W*;
- Al sputtering power – 64 *W*.

Reflectance spectra were measured in the 320 *nm* – 1300 *nm* wavelength range with the Photon RT spectrophotometer. Surface topography was measured using a Dimension Edge atomic force microscope (AFM) (Bruker) in tapping mode, over a 20 *μm* × 20 *μm* scan area. The AFM probe was an Al and diamond-like carbon (DLC) coated Si probe. As roughness evaluation it was calculated rough mean square roughness (Rq).

3. Results and discussion

## 3.1 Optical and physical characteristics investigation

After deposition of samples the reflectance spectra was measured at 8 degrees angle of reflectance. As we can see in (Fig. 8.) our deposited samples all have similar to ordinary shape of silver reflectance.
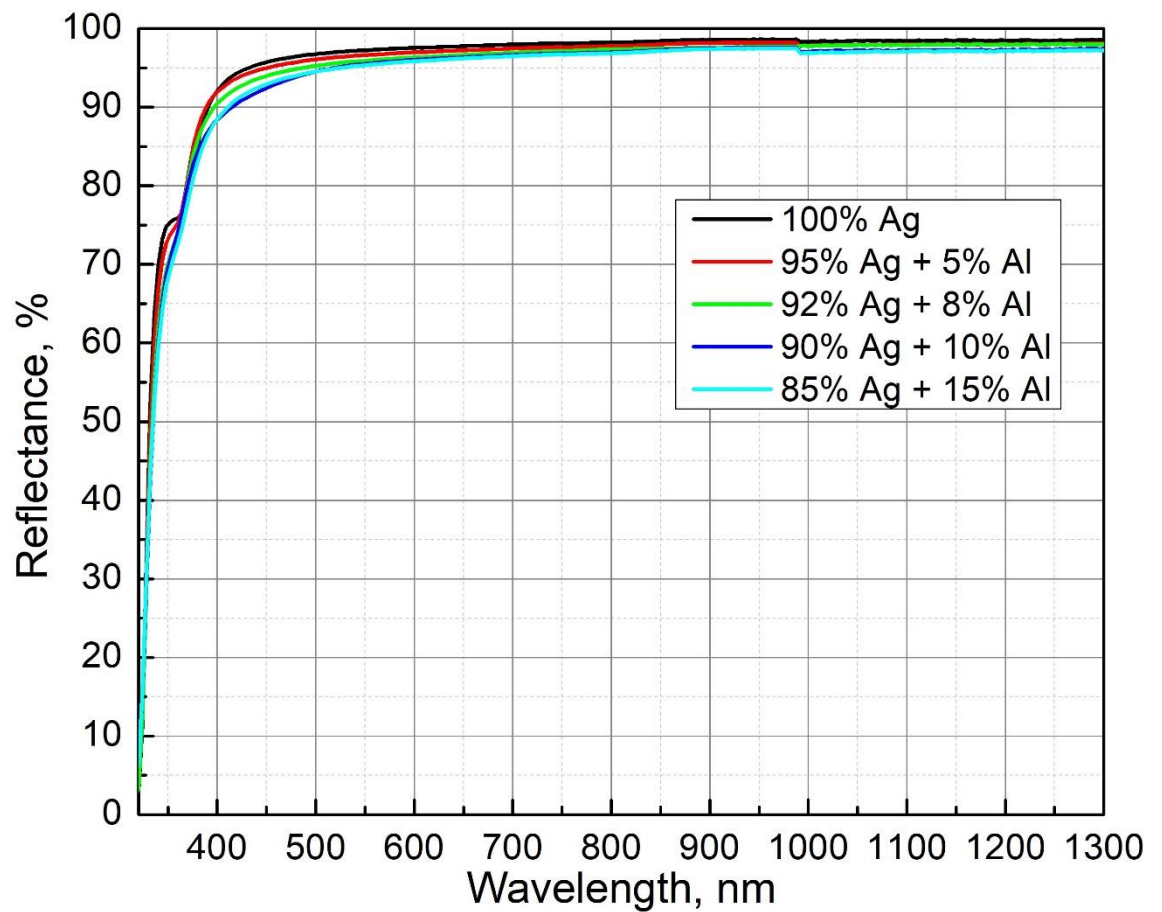
**Fig. 8.** Reflectance spectra of deposited Al-doped silver mirrors.

In reflectance spectra, it is clearly seen that reflectance value decreases with the increasing doping of aluminium. The reflectance drop might be influenced by increased electron-to-atom ratio which red-shifts reflectance spectra due to interband transitions [6]. Similar effect that red-shifts reflectance value might be an increased plasma resonance value. Another mechanism that could influence reflectance decrease is generation of intermetallic phase of Ag_3Al . It appears at higher Al doping values and decreases reflectivity [23].

For more detailed view a region of 320 *nm* – 500 *nm* was chosen to investigate (Fig. 9.). In this region, the reflectance decrease is more clearly viewed. Moreover, it is noticeable that reflectance in the UV region close to 320 *nm* increased with high doping values of aluminium. This minimal reflectance increase could be influenced by original Al reflectivity in this wavelength region.
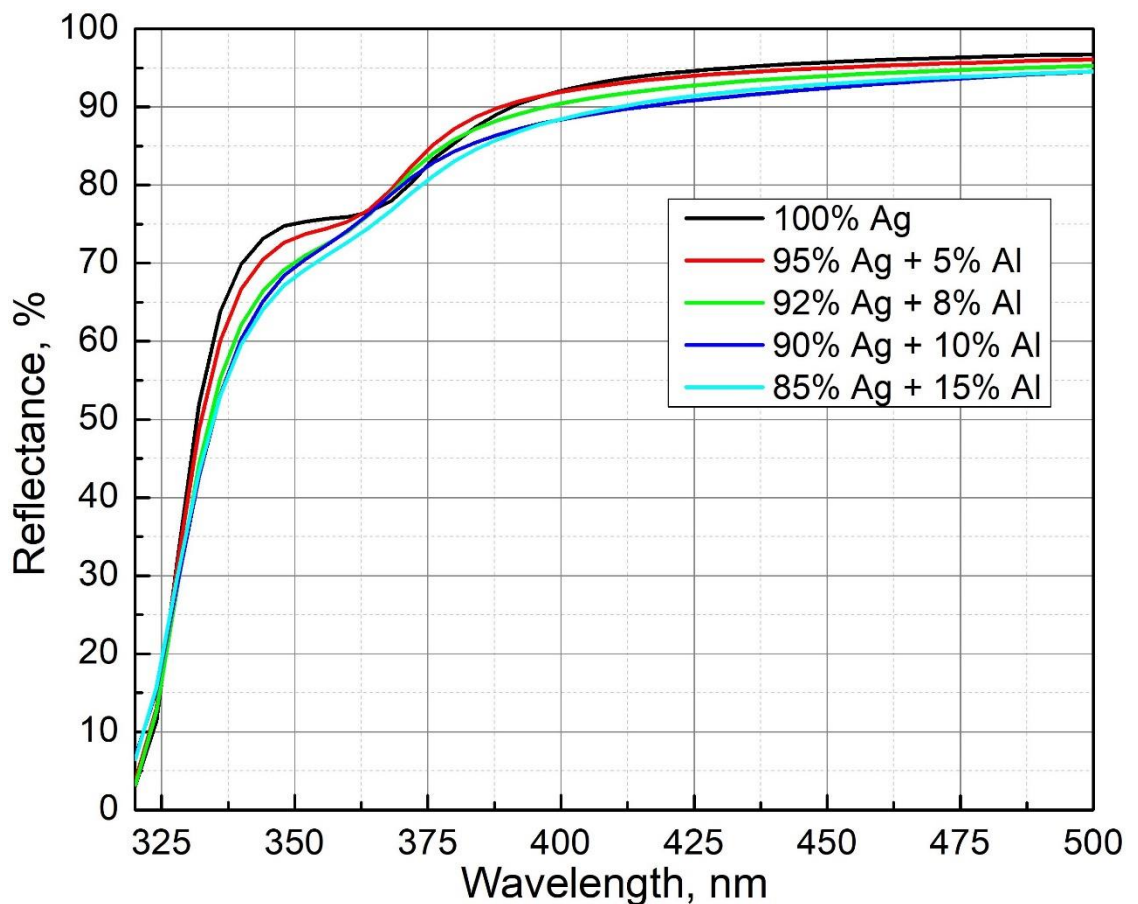
Fig. 9. Zoomed reflectance spectra of deposited samples.

When investigating roughness of the samples (Fig. 10.), it is seen that with the increasing value of Al doping the roughness of the sample decreases. For the sample with 15 % Al doping, the surface roughness is similar to the roughness of bare fused silica substrate.
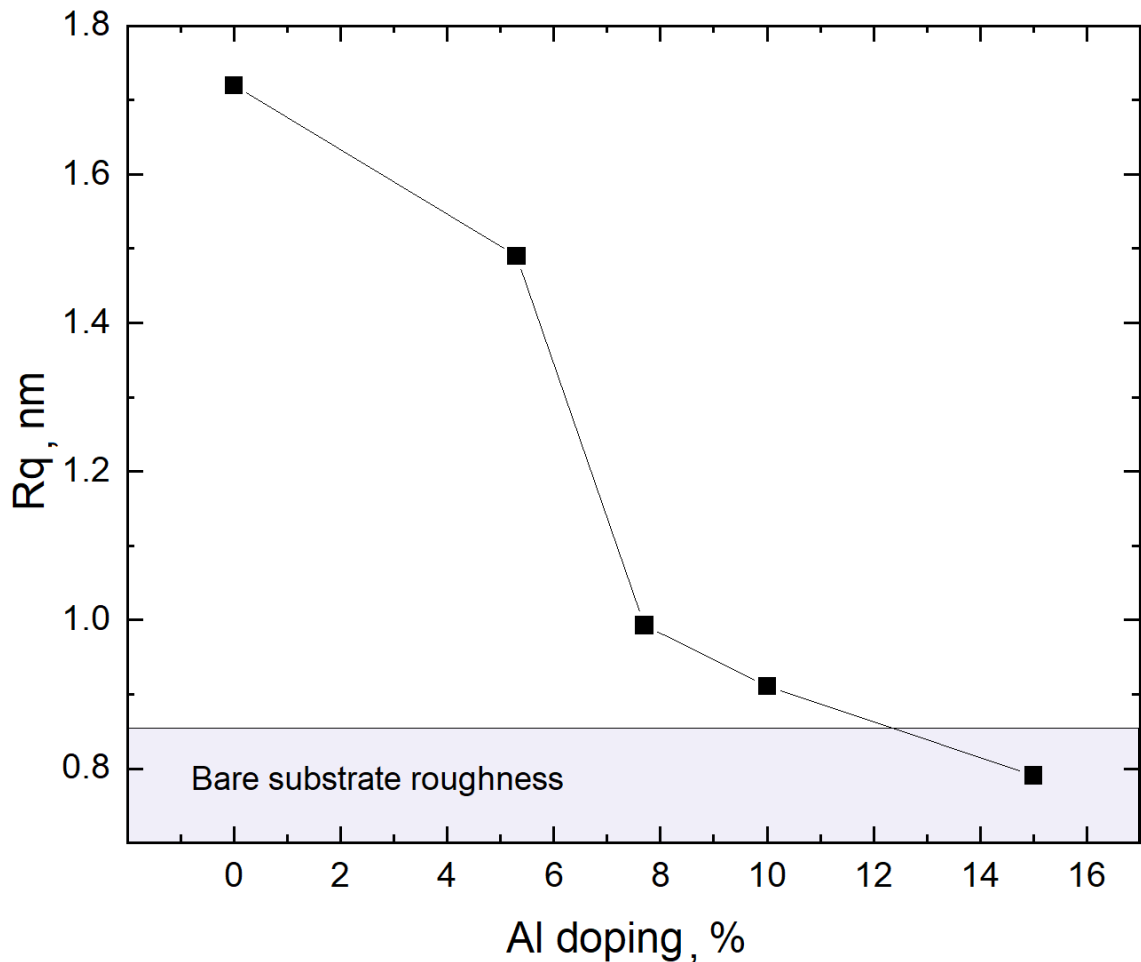
Fig. 10. Roughness values for various Al doped Ag mirror. Values of bare substrate are also shown.

Surface roughness is correlated with reflectance value in the UV region because at shorter wavelengths light scatters more with a rough surface. In our case reflectance value in the UV region decreases with decreasing roughness value. This might be explained that an altered Ag-Al band structure due to Al doping has more influence on mirrors reflectivity in UV than surface roughness decrease [24].

The roughness decrease with the increasing Al doping is associated to property of aluminium grow which tends to be denser structure with smaller particles than Ag. This dense structure growth might be associated with lower Al diffusion rate, because metals with smaller diffusion rate exhibits higher nuclei density and smaller particle size [25].

When analysing reflectance (Fig. 9.), changes at several wavelength were investigated. For the UV region the reflectance decrease is way sharper (Fig. 11.) and this might be influenced by the earlier mentioned mechanisms.
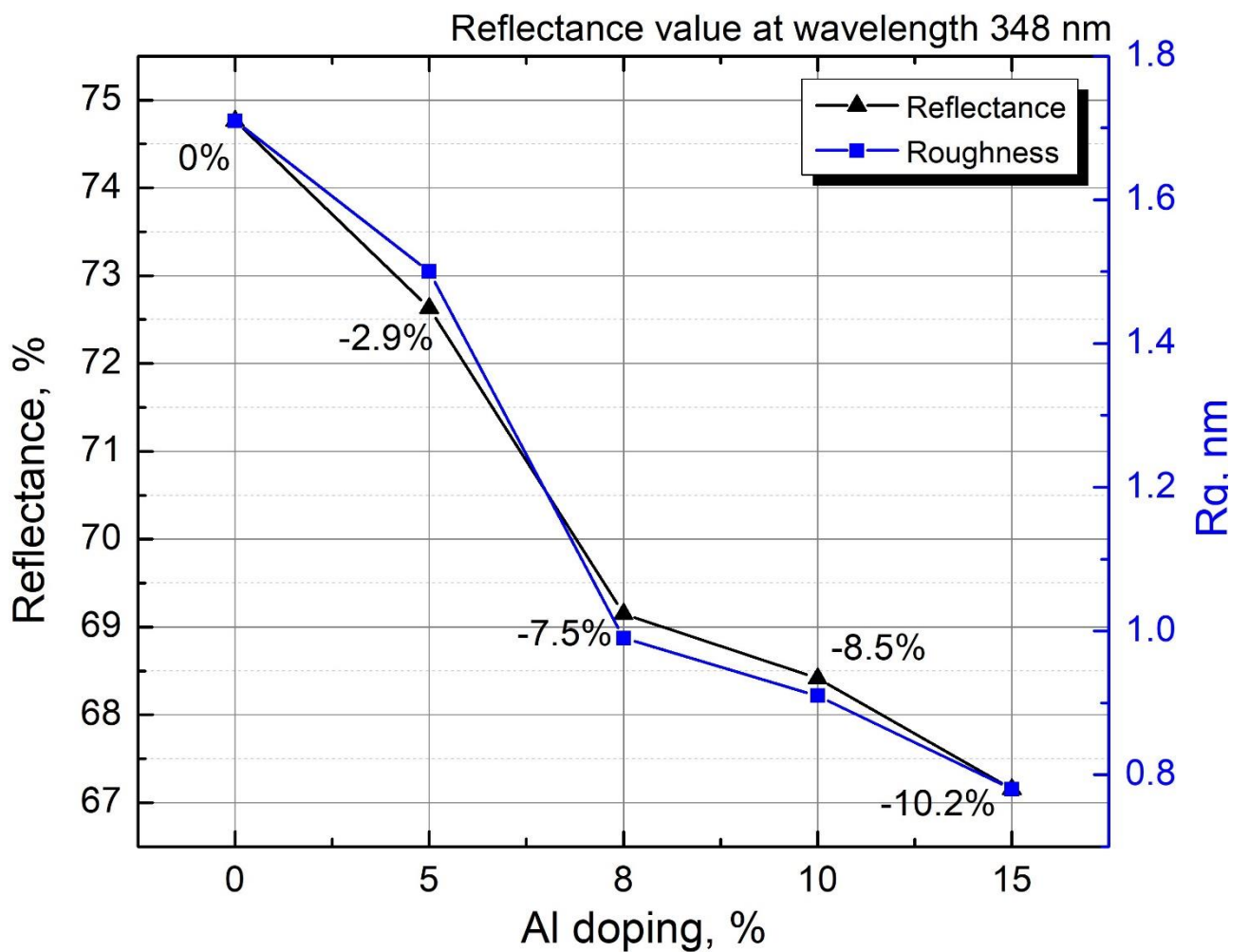

Fig. 11. Reflectance and roughness values dependence from Al doping. Reflectance value are for fixed wavelength at 348 *nm*.

For the VIS region (Fig. 12.) Reflection decrease with increasing Al doping is smaller and might be influenced just by higher doping level of Al and its reflectance value contribution.
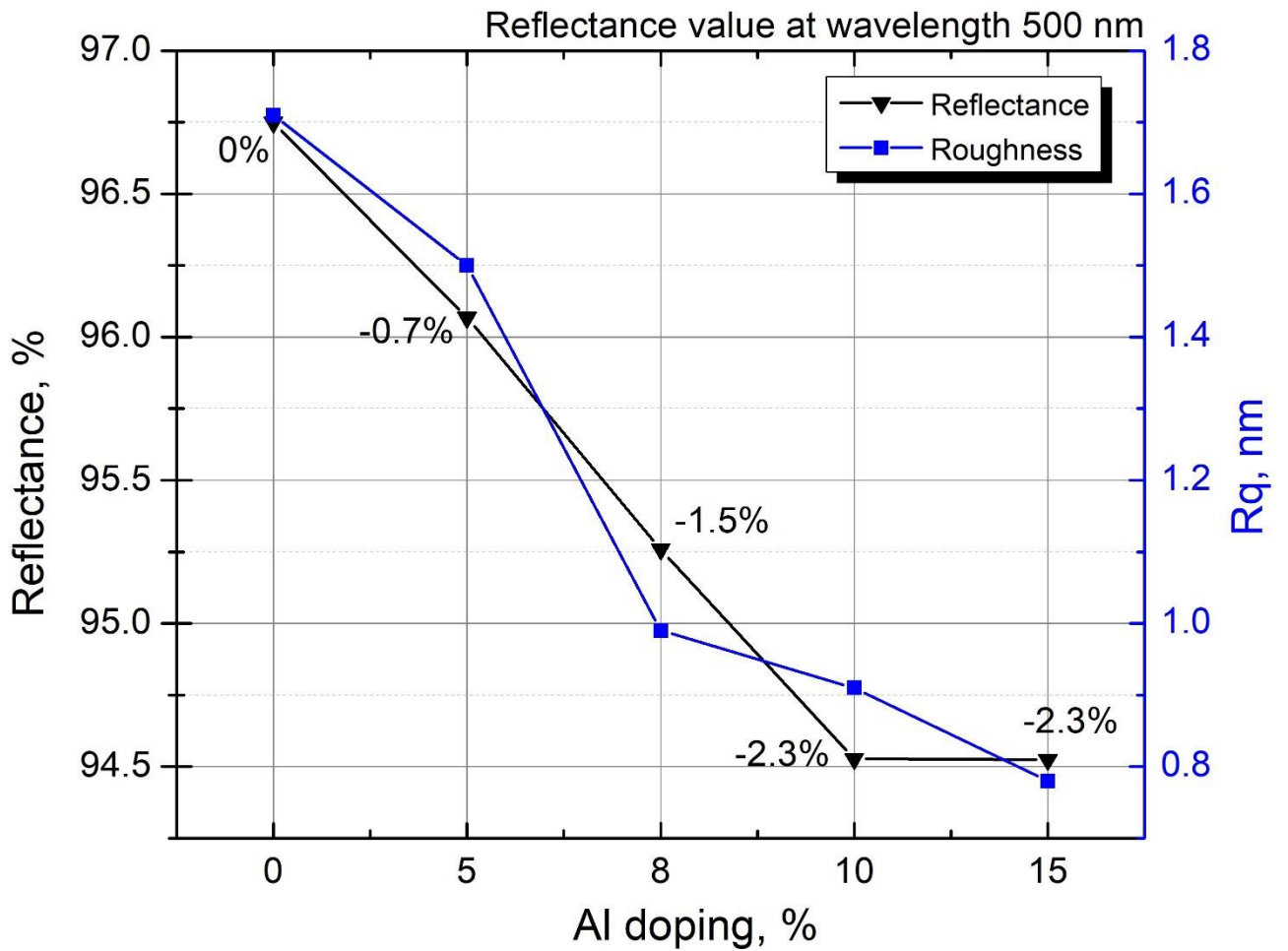

Fig. 12. Reflectance and roughness values dependence from Al doping. Reflectance value are for fixed wavelength at 500 *nm*.

3.2 Radiation test results

Silver mirror samples with 0 % Al, 8 % Al and 10 % Al doping were irradiated with He^+ ions. The reflectance and roughness were measured afterwards.

Due to surface morphology change for highest particle density value, nearly 17 % of reflectance decrease at 400 *nm* region was measured for pure silver mirror (Fig. 13.).
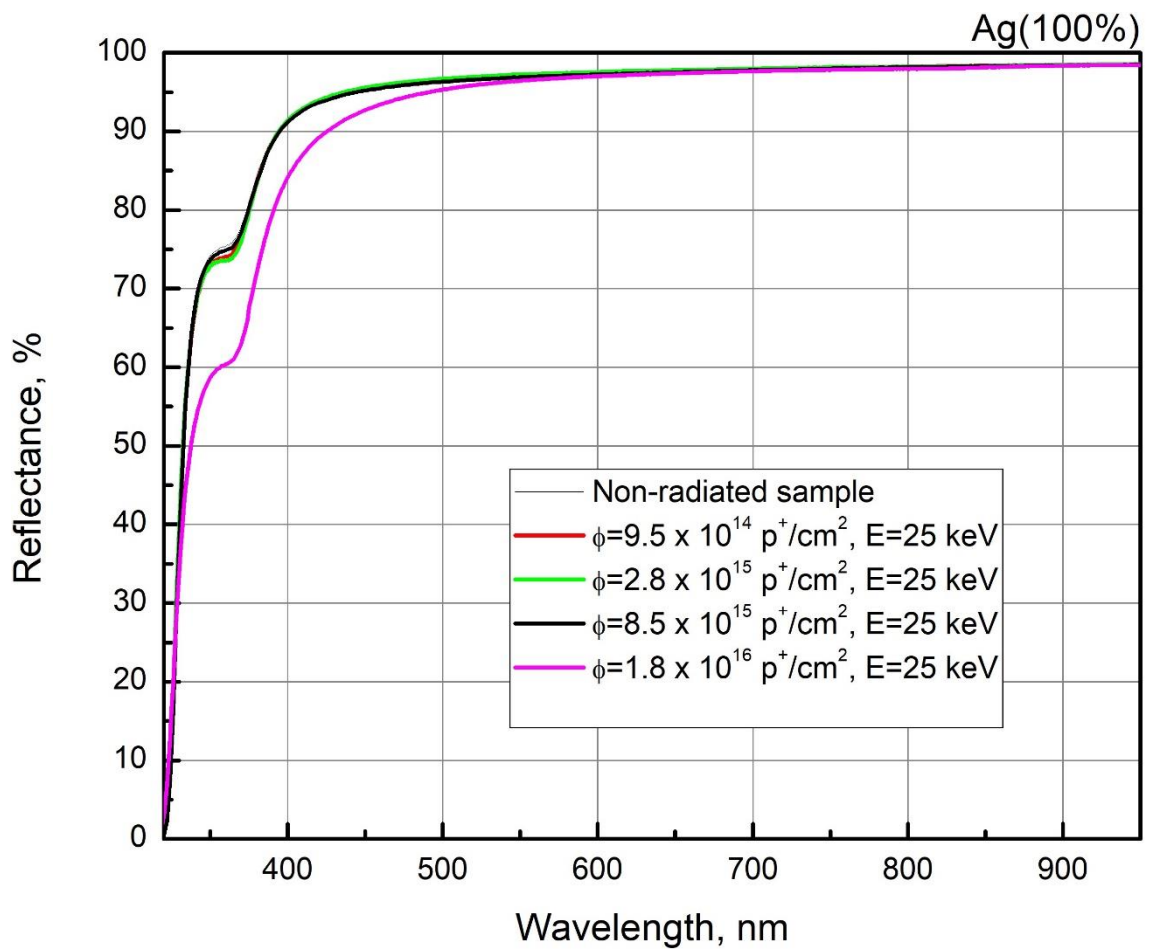
Fig. 13. Reflectance values of the mirror with 0 % Al after radiation test.

Mirror with the 8 % of Al doping (Fig. 14.) optical performance value was effected less and nearly ≈ 14 % reflectance decreased after radiation with helium ions $\phi = 1.8 \times 10^{16} \, p^+/cm^2$.
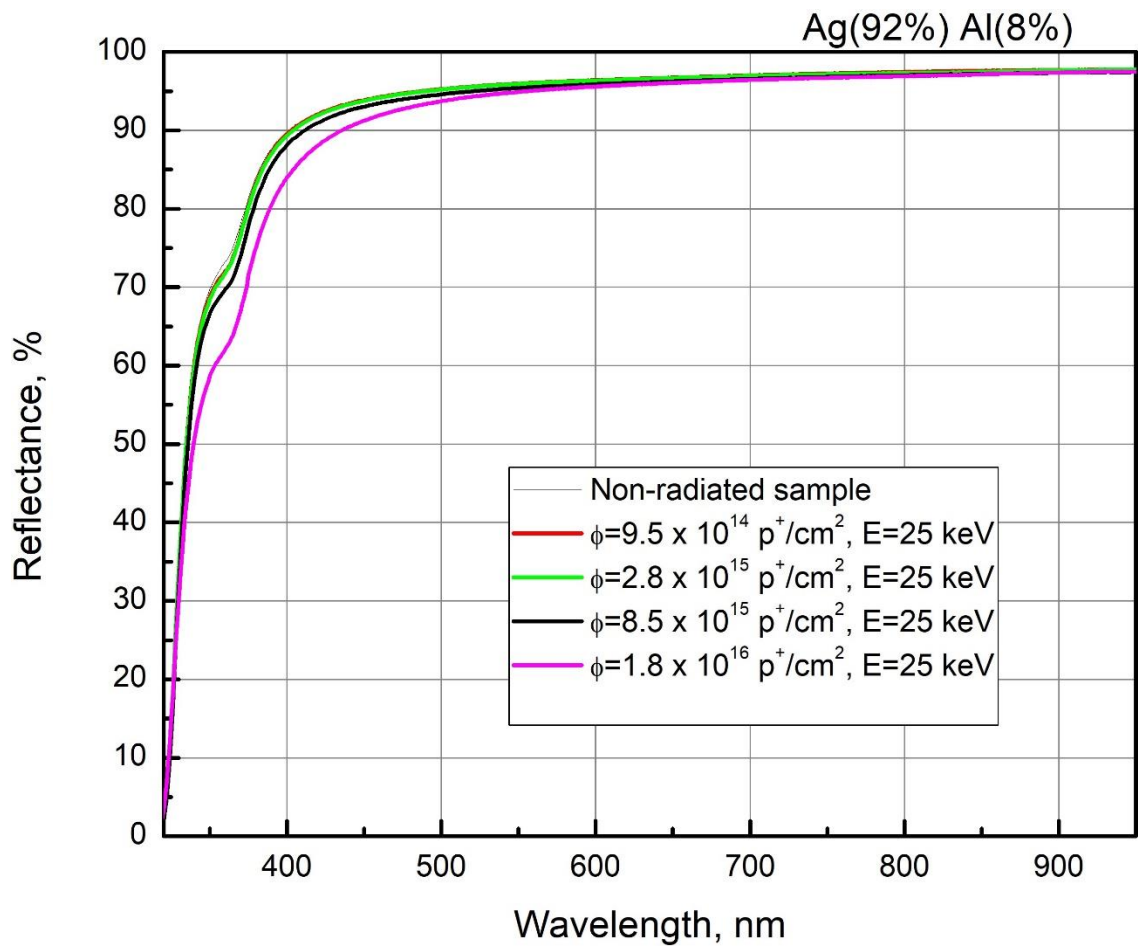
Fig. 14. Reflectance values of the mirror with 8 % Al after radiation test.

The mirrors reflectance with highest Al doping value of 10 % (Fig. 15.) was effected the most, for $\approx$ 28 % reflectance value decrease. These reflectance value changes were influenced by He^+ ions implantation in to the surface of the mirror and initiating certain morphological or structural changes.

Overall reflectance stability and radiation resistance for lower ionized particle density values was seen in all samples (Fig.16.). Least reflectance decrease showed mirror with 8 % Al doping level.
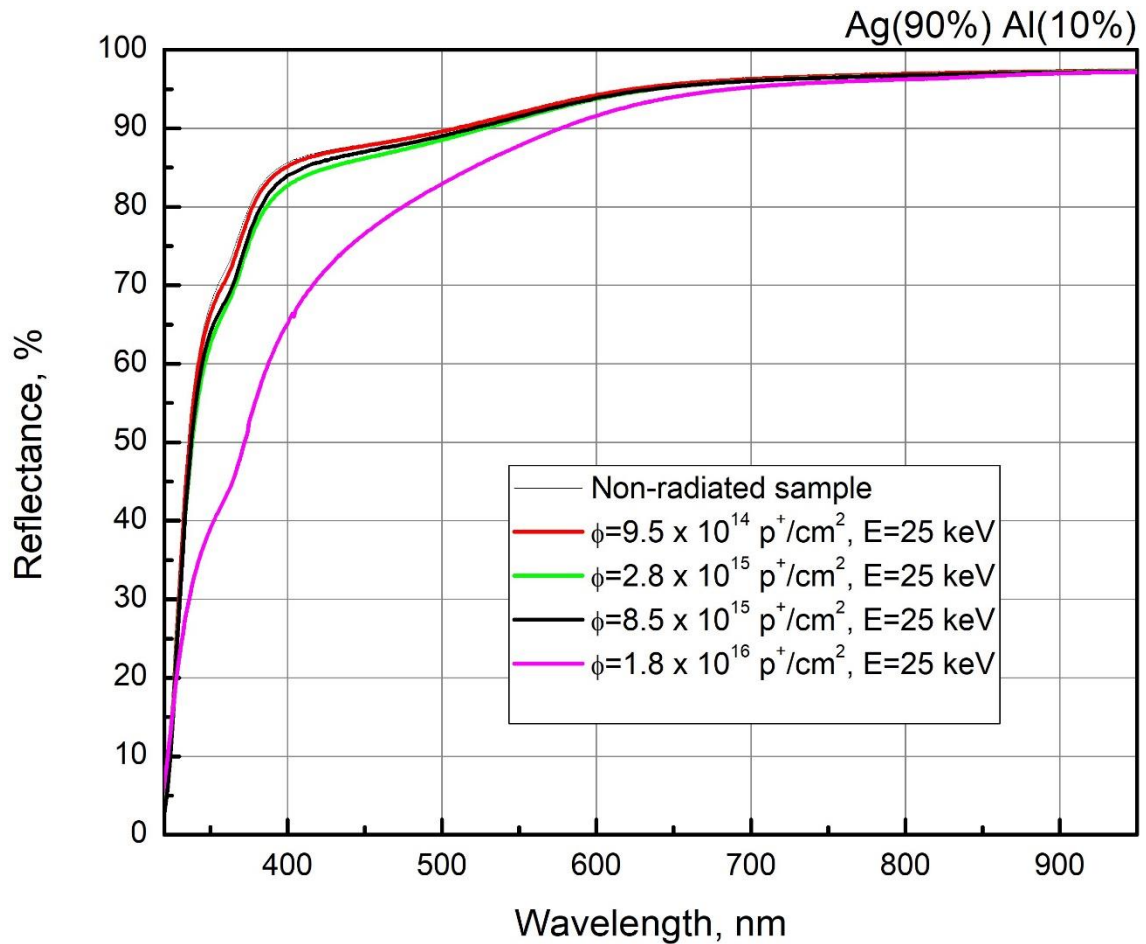
Fig. 15. Reflectance values of the mirror with 10 % Al after radiation test.

After the radiation tests and analysing reflectance, it was noticed that for lower particle densities, mirrors withstood the test without major reflectance changes (Fig. 16.). When radiated with the highest particle density, deciding change in surface structure was done that resulted high reflectance values decrease.
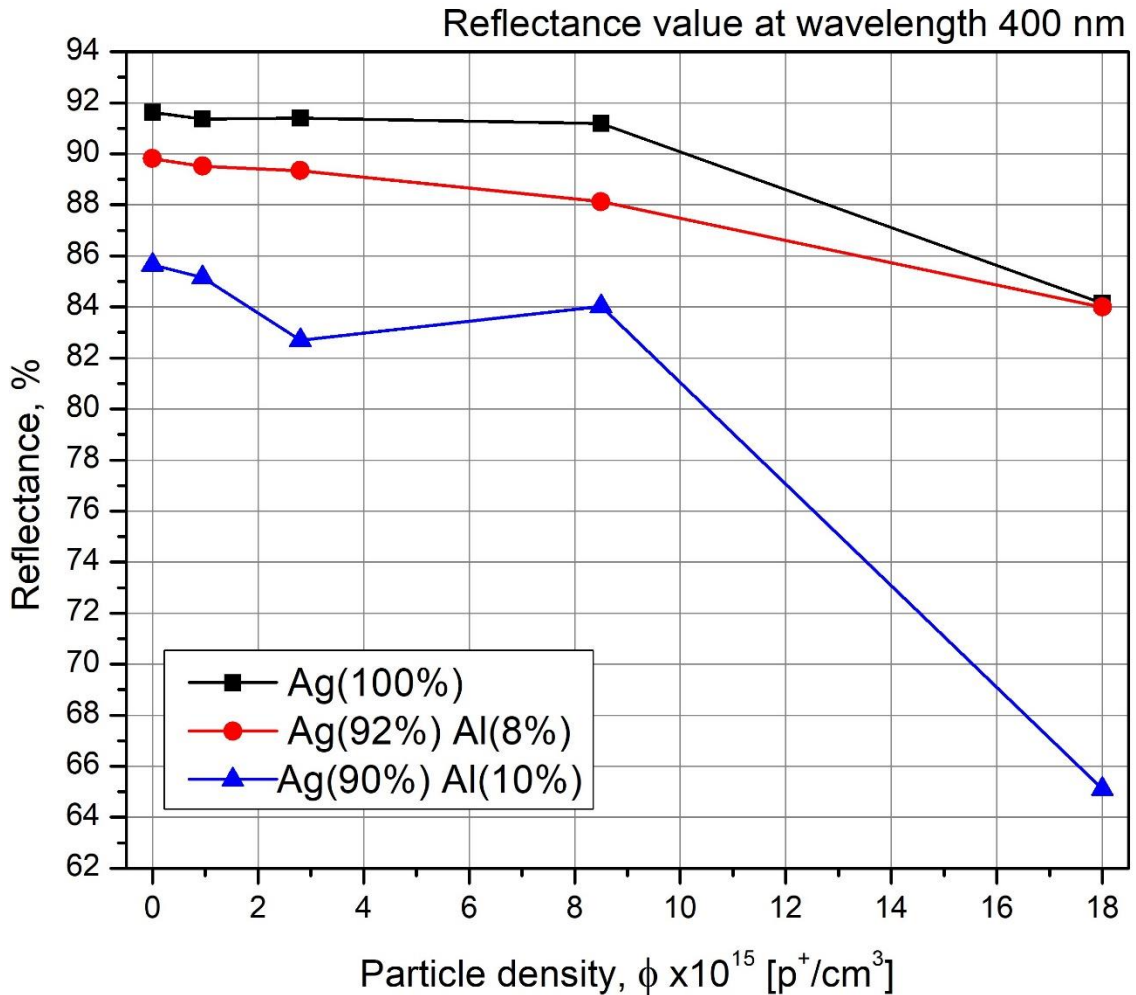

Fig.16. Radiation influenced reflectance values for different Al doping levels.

The highest decrease of reflectivity for 10% Al was most likely associated not with roughness change after radiation test, but with unwanted compounds forming like intermetallic phase of Ag_3Al [23]. Which was likely initiated after elastic collisions with the surface and a high flux of helium ions that lead to an increase in the temperature on the mirrors surface [11].
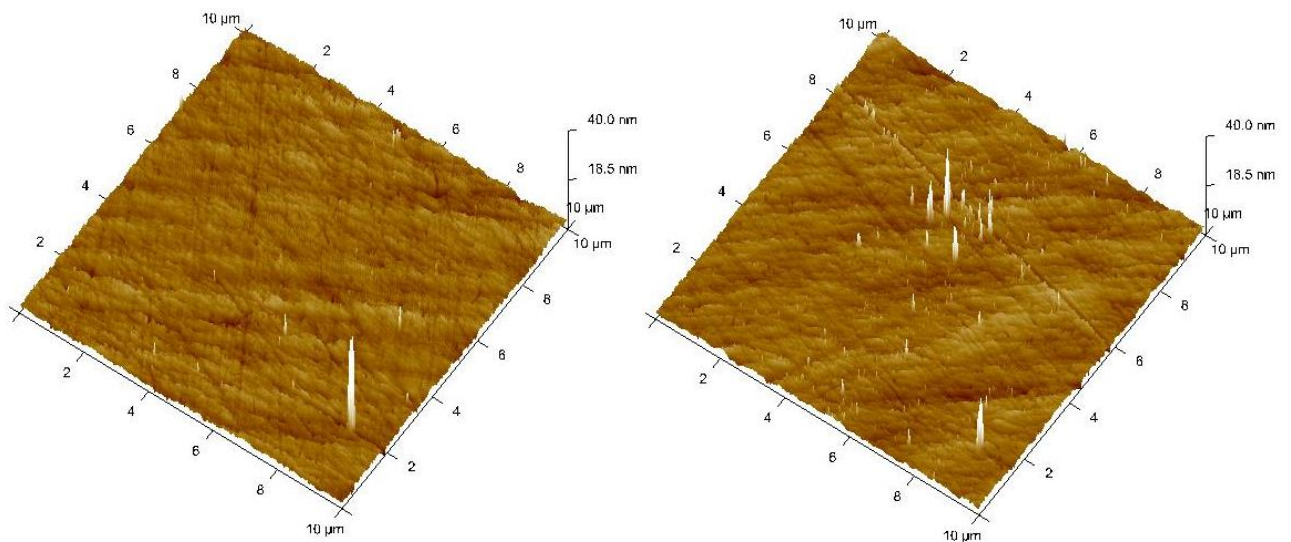
Further surface morphology change was investigated by AFM

3.3 Radiated samples roughness investigation

For pure Ag sample, some structures appeared, reaching the height of 30 *nm* (Fig. 17). The root mean square value of 2.7 *nm* was acquired.
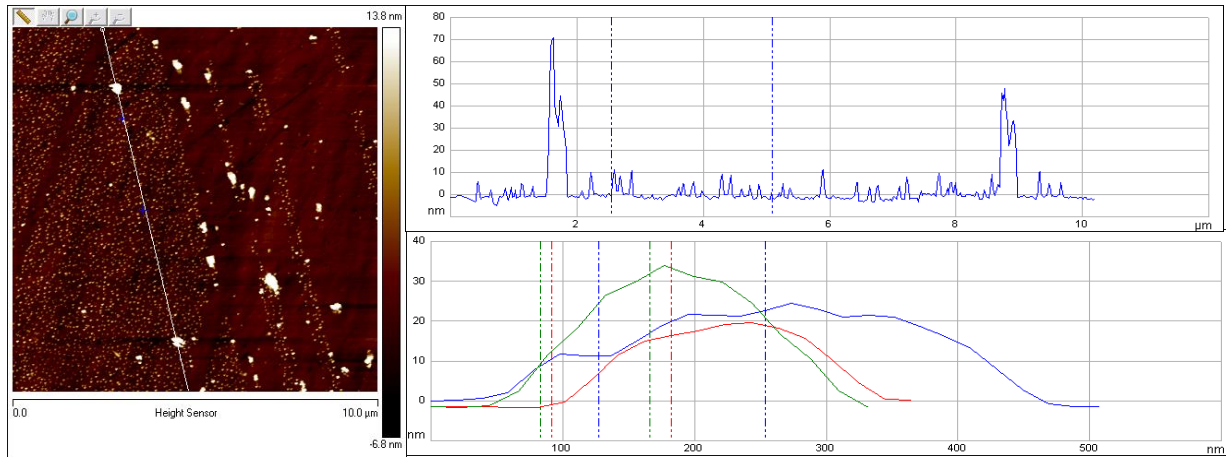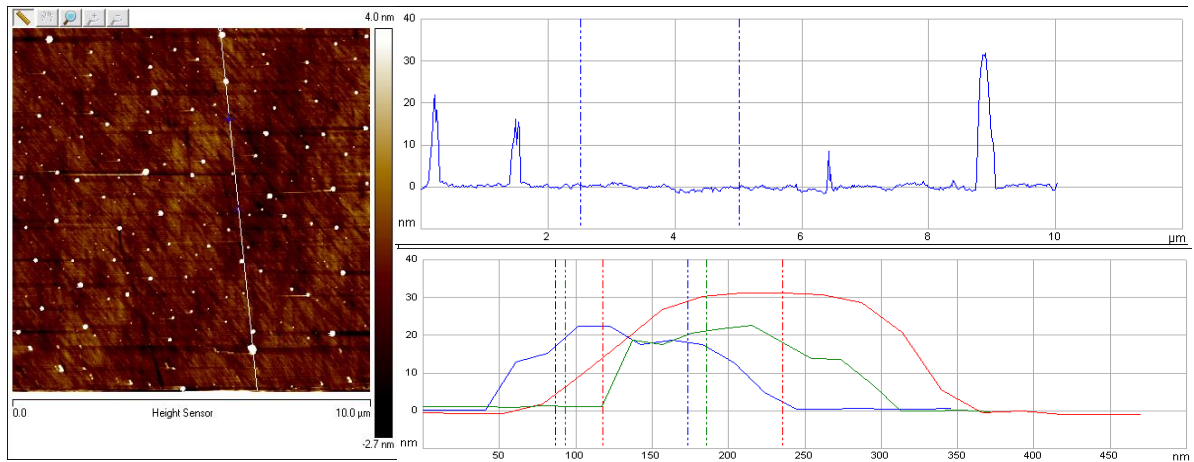

Fig. 17. AFM measurement of 0 ‰ Al mirrors surface after radiation with highest particle density value.

Fig. 18. AFM measurement of 0 ‰ Al mirrors surface before (left) and after (right) with highest particle density value.

Surface roughness of 8 ％ Al mirror was measured, Rq – 1.2 *nm* (Fig. 19).

Fig. 19. AFM measurement of 8 ％ Al mirrors surface after radiation with highest particle density value.
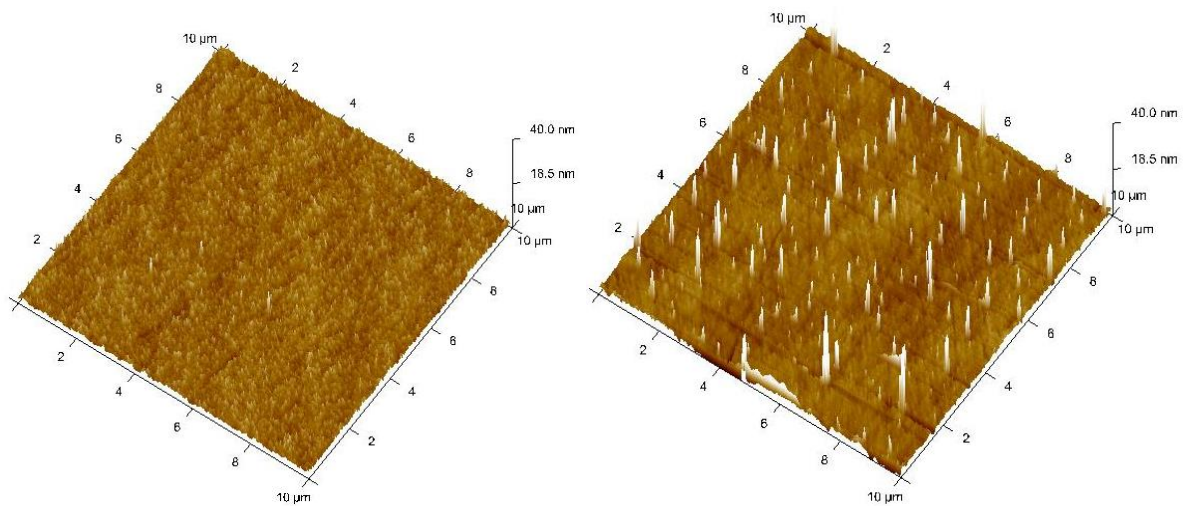

Fig. 20. AFM measurement of 8 ％ Al mirrors surface before (left) and after (right) with highest particle density value.

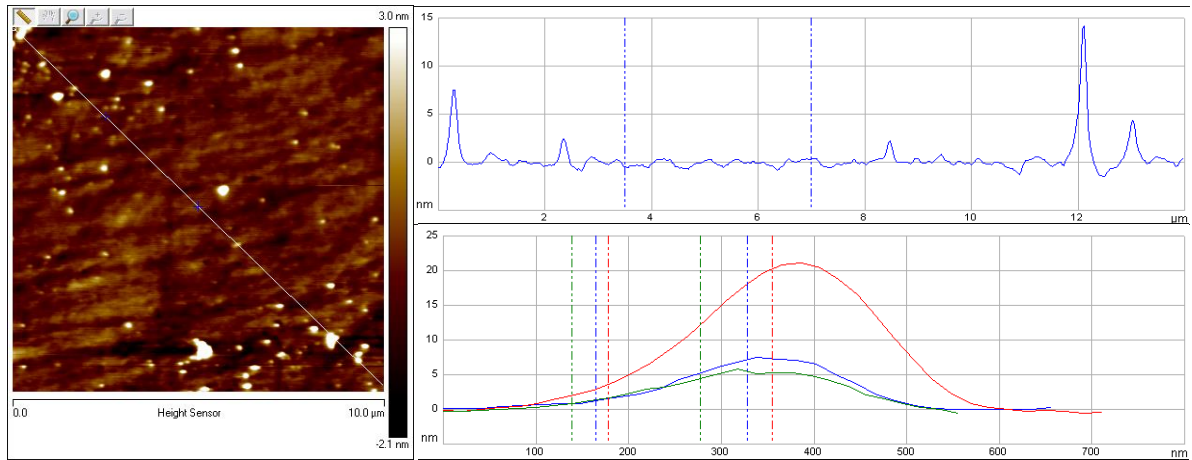Surface roughness of 10 ﹪Al mirror was measured, Rq – 0.73 *nm* (Fig. 21).

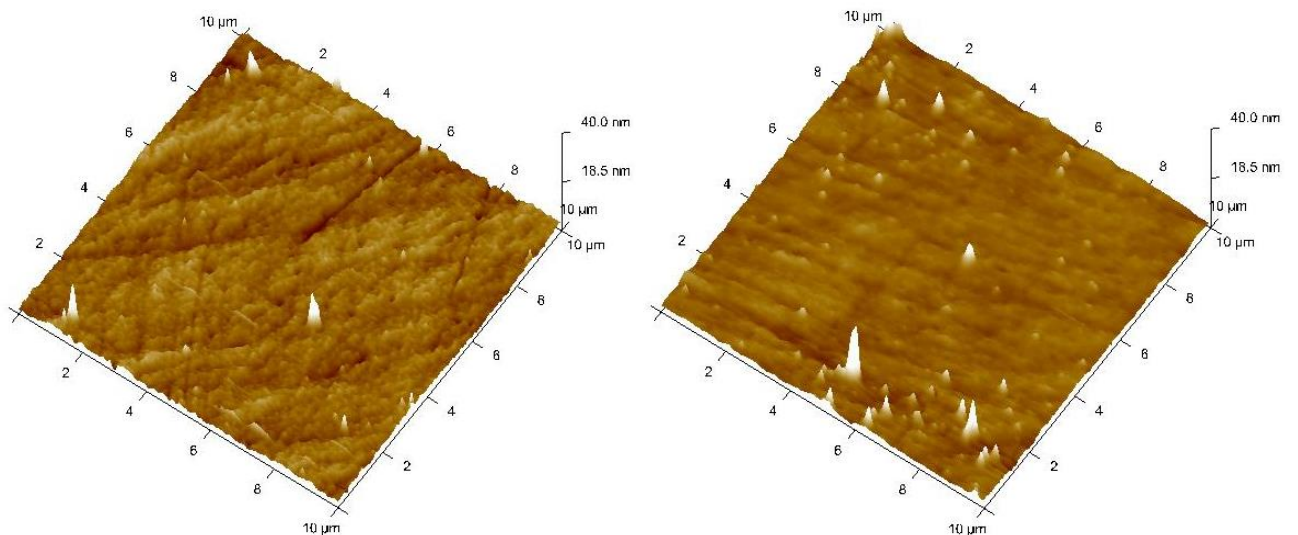**Fig. 21.** AFM measurement of 10 ﹪Al mirrors surface after radiation with highest particle density value.

Fig. 22. AFM measurement of 10 ﹪Al mirrors surface before (left) and after (right) with highest particle density value.

Increase in surface roughness is observed when comparing same samples before and after radiation test (Fig. 23).
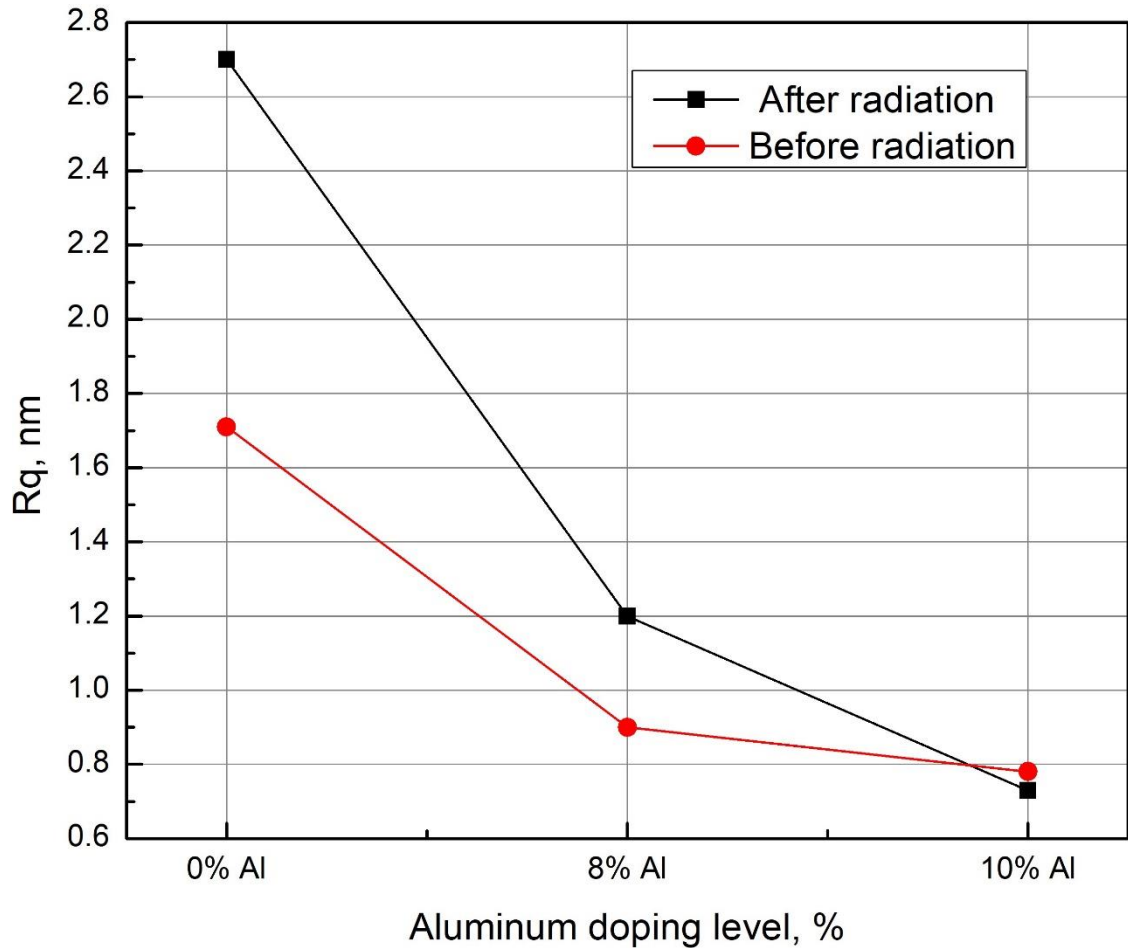
Fig. 23. Roughness value dependence from Al doping level before and after radiation test with highest particle density $\phi = 1.8 \times 10^{16} \; p^+/cm^2$.

Mirrors with Al doping had significantly less surface roughness decrease making them more physically resistant to radiation (Fig. 23). The main mechanism which might have increased surface roughness is shallow penetration of accelerated helium ions up to 100 *nm* of the mirror's surface. Due to the recombination of protons inside the reflective layer H_2 bubbles form hillock structures (Fig. 17, 19, 21) which increase roughness [11].

Results and conclusions

1. An increase of Al content up to 15 % in Ag-Al films beneficially reduced surface roughness, nevertheless it leads to the decrease of reflectance in the UV region. Higher Al content is deleterious due to an altered band structure which is associated with greater reflectivity loss in the UV region;

2. The surface roughness of the Ag-Al mirrors decreased with an increase of Al content from Rq = 1.7 *nm* (0 % Al) to Rq = 0.8 *nm* (15 % Al). It happens because Al has a smaller diffusion than Ag, and such metals exhibit higher nuclear density and smaller particle size;

3. All the samples withstood the radiation up to the $\phi = 8.5 \times 10^{15} \, p^+/cm^2$, E = 25 *keV*. They might be successfully used in various space missions. At the fluence of $\phi = 1.8 \times 10^{16} \, p^+/cm^2$, E = 25 *keV* all the samples had a decrease in reflectance and an increase in roughness;

4. In the current investigation, it was found that the optimum concentration of Al doping is 8 %. In this case, surface roughness was reduced by $\approx$ 52 % compared to pure Ag mirror, and the reflectance decreased only by $\approx$ 1.5% in the VIS region. Such mirrors might be used in space missions with a more energetic particle environment to reflect heat radiation.

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Summary

In this work, the influence of aluminum doping on silver mirrors was investigated. The main parameters observed were the reflection coefficient of the mirrors and the surface roughness. The coating of Ag-Al (silver-aluminum) mirrors was deposited using a magnetron sputtering system from the *Kurt J. Lesker Company*. The coating layer structure of the differently doped mirrors was maintained the same and the thickness of the reflective layer was the same for all specimens at - 150 *nm*. To investigate the dependence of the optical and physical parameters of Ag-Al mirrors on the level of Al doping, the aluminum concentrations of five different samples were used – 0 %, 5 %, 8 %, 10 %, and 15 %. In the study of the resistance of deposited samples to accelerated helium ions, the particle density (ϕ) was varied - $9,5 \times 10^{14} \, p^+/cm^2$, $2,8 \times 10^{15} \, p^+/cm^2$, $8,5 \times 10^{15} \, p^+/cm^2$ ir $1,8 \times 10^{16} \, p^+/cm^2$, with $E = 25 \, keV$.

A decrease in the surface roughness from Rq = 1.7 *nm* (0 % Al) to Rq = 0.8 *nm* (15 % Al) was observed with increasing Al doping in the silver coatings. This effect happened due to the properties of Al to form denser and smaller atomic structures. Along with the surface roughness, the value of the reflection coefficient of the mirrors decreased. Reflection decrease depends on the structure alteration of the silver valence band which is effected by Al doping. This effect of reflectance decrease is most dominant in the UV and VIS areas, which was also observed in the course of this work.

In the study of the radiation resistance of Ag-Al mirrors to the space environment, different values of helium ion particle density were chosen, and the maximum value corresponds to the density of particles affecting optical coatings in space for more than five years. A significant change in the reflectance value of the mirrors was observed only at a highest value of particle density $\phi = 1,8 \times 10^{16} \, p^+/cm^2$, and in this experiment, the surface roughness changed the least in the sample with 8 % Al doping.

The change in the roughness of the speciments was caused by the implanted helium ions, which recombine and form hillock structures with a height of ≈ 30 *nm* inside the reflective layer. The sample with the lowest surface roughness value decrease after radiation tests, was 8 % Al doped mirror. This mirror could be successfully applied for space missions in optical systems, even under energetically difficult conditions.

Santrauka

Šiame darbe buvo ištirta aliuminio legiravimo įtaka sidabro veidrodžiams. Pagringiniai stebėti parametrai buvo veidrodžių atspindžio koeficientas ir paviršiaus šiurkštumas. Ag-Al (sidabro-aliuminio) veidrodžių danga buvo nusodinta naudojant *Kurt J. Lesker Company* magnetroninio dulkinimo sistemą. Skirtingai legiruotų veidrodžių dangų sluoksniai buvo išlaikyti vienodų fizikinių matmenų ir atspindinčio sluoksnio storis visiem bandiniam buvo vienodas – 150 *nm*. Tiriant Ag veidrodžių optinių ir fizikinių parametrų priklausomybę nuo Al legiravimo lygio, naudota penkių skirtingų bandinių aliuminio koncentracija - 0 %, 5 %, 8 %, 10 % ir 15 %. Tiriant nusodintų bandinių atsparumą įgreitintiems helio jonams, dalelių tankis ϕ buvo keistas - $9,5 \times 10^{14} \, p^+/cm^2$, $2,8 \times 10^{15} \, p^+/cm^2$, $8,5 \times 10^{15} \, p^+/cm^2$ ir $1,8 \times 10^{16} \, p^+/cm^2$, o $E = 25 \, keV$.

Didinant Al legiravimo kiekį sidabro dangose pastebėtas paviršiaus šiurkštumo mažėjimas nuo Rq = 1,7 *nm* (0 % Al) iki Rq = 0,8 *nm* (15 % Al). Šis efektas įvyko dėl Al savybių optinėje dangoje suformuojant tankesnes ir mažesnio dydžio atomines struktūras. Kartu su paviršiaus šiurkštumu mažėjo ir veidrodžių atspindžio koeficiento vertė, kuri priklauso nuo aliuminio paveiktos sidabro valentinės juostos struktūros. Šis efektas ryškiausiai pastebimas UV ir VIS srityse, kas buvo stebima ir šio tyrimo eigoje.

Tiriant Ag-Al veidrodžių atsparumą kosmoso aplinkai, buvo pasirinktos skirtingos dalelių tankio vertės, o maksimali vertė atitiko daugiau nei penkių metų darbo kosmose optines dangas paveikiančių dalelių tankį. Reikšmingas veidrodžių atspindžio vertės pokytis buvo stebimas tik esant dalelių tankiui $\phi = 1,8 \times 10^{16} \, p^+/cm^2$, o šio eksperimento metu paviršiaus šiurkštumas mažiausiai pasikeitė bandinio su 8 % Al legiracija.

Bandinių šiurkštumo pokytį lėmė implantuoti helio jonai, kurie rekombinavę atspindinčio sluoksnio viduje formuoja iškilias struktūras, kurių aukštis siekė ≈ 30 *nm*. Mažiausią paviršiaus šiurkštumo vertę išlaikęs bandinys su 8 % Al legiracija galėtų būti sėkmingai taikomas kosmose naudojant optinėse sistemose, net ir energetiškai sudėtingomis sąlygomis.