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Long term durability of protected silver coating for the mirrors of Ariel mission telescope

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ABSTRACT

Ariel (Atmospheric Remote-sensing Infrared Exoplanet Large survey) is the fourth medium-size mission in ESA "Cosmic Vision" program. It is scheduled to launch in 2029. Ariel will conduct spectroscopic and photometric observations of a large sample of known exoplanets to survey their atmospheres with the transit method.

Ariel is based on a 1 m class telescope designed for the visible and near infrared spectrum, but optimized specifically for spectroscopy in the waveband between 1.95 and 7.8 µm. Telescope and instruments will be operating in cryogenic conditions in the range 40–50 K.

The telescope mirrors will be manufactured in aluminum 6061, with a protected silver coating deposited onto the optical surface to enhance reflectivity and prevent oxidation and corrosion.

During the preliminary definition phase of the development work, leading to mission adoption, a silver coating with space heritage was selected and underwent a qualification process on disc-shaped samples of the mirrors substrate material. The samples were deposited through magnetron sputtering and then subjected to a battery of tests, including environmental durability tests, accelerated aging, cryogenic tests and mechanical resistance tests. Further to the qualification, the samples have been stored in cleanroom conditions and periodically re-examined and measured to detect any sign of coating degradation.

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The test program, still ongoing at the time of writing this article, consists of visual inspection with a high intensity lamp, spectral reflectance measurements and Atomic Force Microscopy (AFM) evaluation of nanometric surface features.

The goal is to ensure stability of the optical performance, in terms of coating reflectance, during a time span comparable to the period that the actual mirrors of the telescope will spend in average cleanroom conditions.

This study presents the interim results after three years of storage.

Keywords: space telescope, Ariel mission, aluminum mirror, silver coating, coating durability, thin films, optical properties

1. INTRODUCTION

Ariel is the fourth medium-class mission under development in the framework of ESA "Cosmic Vision" Program. It was adopted in 2020 and launch is planned for 2029. During its 4-year of nominal mission duration, Ariel will conduct a survey of known exoplanets to characterize their atmospheres through transit spectroscopy and photometry in the waveband between 0.5 µm and 7.8 µm.[1]

The Ariel telescope is based on an off-axis, unobscured Cassegrain design with an elliptical primary mirror with an aperture of 1100 mm (major axis) and 768 mm (minor axis), corresponding to a light collecting area of approximately $0.6\,m^2$. The telescope was designed to be diffraction limited at the wavelength of 3 µm on a 30″ field of view.[2] The required average telescope throughput is 96 %.[3] Telescope and instruments will operate at a temperature below 50 K.

Following the heritage of the JWST MIRI instrument,[4] aluminum alloy 6061 in the T651 forge has been chosen for mirrors substrates and supporting structures of the telescope, after a trade-off study[5] on manufacturability and cost.

To comply with throughput requirements, particularly in the visible portion of the operating waveband, and to protect the aluminum substrate from oxidation, the Consortium decided to apply a protected silver coating to the telescope mirrors.

The coating, from CILAS[*] is qualified for space, but needed to be subjected to additional qualification tests to assess performance at the Ariel telescope operating temperature of <50 K and because of the large size of the primary mirror, raising possible concerns on the uniformity of the deposition process and stability of the coating.

An initial study was therefore devised to test optical performance and durability on Al6061-T651 substrates, consisting of a qualification campaign on coated aluminum samples,[6,7] and a verification test on additional samples and on a full-scale demonstrator of the Ariel primary mirror denoted Pathfinder Telescope Mirror (PTM).[8]

After the successful completion of the qualification, the samples have been kept in storage in an cleanroom facility (ISO6), and are being periodically re-examined to detect signs of functional (reflectance) or visual deterioration due to oxidation or delamination.

Silver coatings, although protected by a capping layer, Can be sensitive to damaging from contact with humidity, sulfur and chlorine pollutants, normally present even in the controlled atmosphere of a cleanroom.[9] It is therefore necessary to ensure that the coating will not deteriorate in the time span from deposition on the Ariel telescope mirrors to launch.

2. MATERIALS AND PROCESSES

2.1 Samples Description

The coating qualification campaign was performed on several samples of Al 6061-T651 in rolled plate form, the same aluminum alloy and forge currently foreseen for Ariel Telescope mirrors and supporting structure.

[*]CILAS-ArianeGroup, Etablissement de Marseille, 600 avenue de la Roche Fourcade, Pôle ALPHA Sud - Z.I. Saint Mitre, 13400 Aubagne, France

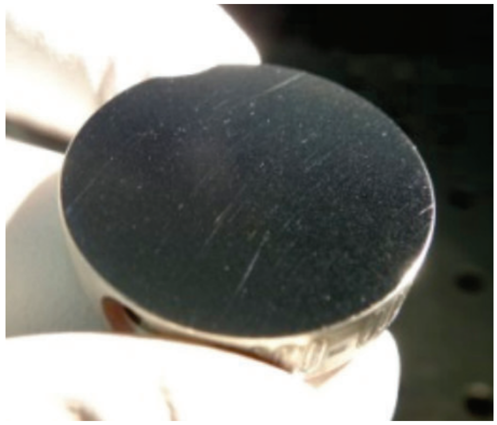

Figure 1. Picture of one of the aluminum samples during a visual inspection before coating.

The samples are shaped as discs of 25 mm of diameter and 6 mm thick (Figure 1 shows one of the samples being held for visual inspection before the coating run). The samples were procured, polished and cleaned by MediaLario[†] before delivery to CILAS for coating. Roughness of the optical surface was measured with a Taylor Hobson CCI White Light Interferometer on areas measuring 1.5 mm × 1.5 mm and 300 µm × 300 µm. All samples were within the 10 nm RMS specification.

The qualification campaign (in fact, a *delta*-qualification), consisted in a series of environmental and mechanical resistance tests to ensure that the coating will reach the end of life of the instrument without significant performance degradation, following the European Cooperation for Space Standardization (ECSS) Q-ST-70-17C standard.[10] A brief description of the set of tests is reported in Table 1. The qualification program was overall successful.[6]

Table 1. Summary of specifications of the coating qualification tests performed on the samples.

Test	Specifications
Adhesion	ISO 9211-4, Method 2 Severity 2
Humidity	ISO 9022-2 Method 12 Severity 06, 24 h test duration, 90 % RH, 55±3 °C (no condensation)
Temperature cycling at ambient pressure	ISO 9022-2, 30 cycles, T. range −40 °C to 70 °C
Abrasion resistance	ISO 9211-4, Method 01 Severity 01
Cryogenic cycling in vacuum	ECSS-Q-ST-70-04C, 10 cycles, T. range: 54 K to 293 K, Vacuum: $<1 \times 10^{-4}$ mbar

After the qualification campaing, a subset of the samples was retrieved by the authors and stored in airtight containers in a cleanroom environment (ISO6). The risk of exposure to excessive humidity is further minimized by placing silica gel dessicant bags inside the containers. The samples are being re-examined periodically in a normal laboratory environment.

Table 2 identifies the samples being monitored, coming from two subsequent coating deposition runs: a first test run, performed on April 3rd, 2019, and the actual qualification run, on December 12th, 2019. Both runs were conducted with the nominal coating procedure and produced equivalent results. The set of treatments to which each sample was subjected during the qualification is also reported in the table.

All verification and measurements described in this paper have been performed on all samples listed Table 2, but for the reminder of the treatment we will focus on Samples SN01 and SN12, that have been in storage for a

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Table 2. List of samples under test, with coating deposition date and qualification tests performed.

Coating Run	Sample	Humidity	Thermal	Adhesion	Cryotest	Cleaning	Abrasion
03/04/2019	SN01			✓	✓	✓	
	SN12	✓					
12/12/2019	SN-01M						
	SN-02M			✓			
	SN-04M	✓		✓			
	SN-05M		✓	✓			
	SN-06M			✓	✓		
	SN-07M	✓	✓	✓	✓		
	SN-08M	✓	✓	✓	✓	✓	✓
	SN-09M			✓		✓	✓
	SN-10M			✓		✓	✓

longer period, Sample SN06M since it was already examined in details in a previous work[7] and Sample SN08M because it was subjected to the entire set of qualification tests.

2.2 Coating Process

The coating process employed by CILAS for the samples is based on physical vapor deposition. The coating platform consists in a large magnetron sputtering chamber. Samples are inserted on a tray sliding beneath a set of cathodes.[11] The process is suited to optical substrates up to 2 m by 2 m of footprint and 0.4 m of thickness.[12]

The protected silver coating described in this paper is on average 350 nm thick, with a thickness uniformity measured at 10 %.

The structure of the stack is illustrated in Figure 2 and consists of at least three layers: a NiCr adhesion layer of less than 10 nm of thickness, the reflecting silver layer, and a dielectric capping and protection layer. An additional intermediate adhesion layer may be present between the silver and the capping layer. The actual layers thicknesses and composition of the coating cannot be disclosed due to business confidentiality.

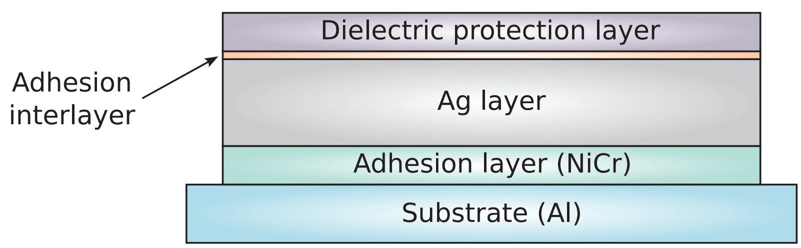

Figure 2. Indicative structure of the multilayer coating stack. The total coating tickness is approximately 350 nm.

3. VERIFICATION METHODS

The ECSS Q-ST-70-17C standard[10] defines a set of verification and acceptance criteria to be performed on coatings to assess their performance and compliance with requirements.

More specifically, after each test, the coating shall present:

1. no visual degradation;
2. no delamination or adherence loss;
3. thickness according to requirements;
4. performance measurements compliant with coating specifications.

The following paragraphs describe the assessment methods employed to verify compliance of the samples under test according to the list above, except for item 3 (thickness) since it was already verified during qualification and it is not expected to be affected by storage.

3.1 Relative Reflectance Measurements

Immediately after coating deposition, the reflectance of all samples was measured by the manufacturer with a Perkin-Elmer Lambda 950 spectrophotometer with a reflectometry accessory, in the waveband 500 nm to 2500 nm. Accuracy, as reported in the instrument datasheet, is $\pm 0.6\,\%$ from 500 nm to 890 nm and $\pm 1\,\%$ above 890 nm.

Subsequent relative reflectance measurements were taken at the Institute for Photonics and Nanotechnologies of the National Research Council (CNR–IFN) in Padova with a custom built setup. Reproducibility of the measurements in the worst case has been determined to be better than $\pm 1.2\,\%$ over the 500 nm to 900 nm wavelength range, and better than $\pm 3.8\,\%$ over the 400 nm to 1000 nm wavelength range.

In order to cross-calibrate the two setups, which appear to have a measurement bias between each other (see Figure 5 in the *Results* section), we used one of the earliest measurement of Sample SN01 as reference point, since it presented the shortest temporal gap between measurements.

3.2 Visual Inspection

The ECSS standard suggests following Annex C of ISO 9211-4:2022 for Visual Inspection (VI), that mandates the use of two cool white 15 W lamps positioned directly above the sample, and to look at the sample against a black matte background at a distance of $\leq$45 cm and at a near grazing angle.[13] The use of optical micrographs is suggested only in case of suspected degradation, to further qualify it. In our case it was employed to look for signs of oxidation, as explained in Section 4.1.

Darkfield imaging using a compact digital camera (Canon IXUS 220 HS) and a custom built LED lighting setup was also employed to highlight the presence of light scattering defects.

3.3 Atomic Force Microscopy

Besides optical imaging techniques, we employed an Atomic Force Microscope (AFM) for a qualitative analysis of surface topography and to measure surface roughness.

AFM scans were taken with a Park System[‡] XE-Series 70 microscope in non-contact mode and processed with the Gwyddion open source software[14] (the processing pipeline consisted in removal of low spacial frequencies by fitting and subtraction of an x, y third order polynomial surface, rows alignment using "median" as statistic and "scars removal").

4. RESULTS

4.1 Visual Inspection

The optical surface of all samples appeared visually unaltered after the storage period, as exemplified in Figure 3: no discernible signs of coating degradation, such as cracks, blistering or change in color/iridescence, nor other visible signs of delamination could be spotted. In particular, we could not detect signs of oxidation developing from surface grains, as described for example by Folgner *et al.* in their studies of protected silver coatings exposed to mixed flowing gas.[9,15]

Apart from scratches and occasional dust particles, the most prominent features on the optical surface continued to be the glue residues from adhesion tests, especially evident on sample SN01.

It is worth noting that the uncoated back and lateral surfaces of the samples do exhibit a slight brownish coloration and faint whitish areas, compatible with the oxidation of bare aluminum, so the level of exposure to pollutants seems to be at least sufficient to cause slight degradation of the substrate.

Darkfield photographs also show a mostly uniformly dark optical surface, indicative of low scattering (Figure 4).

[‡]Park Systems Inc., KANC 15F, Gwanggyo-ro 109, Suwon 16229, Korea

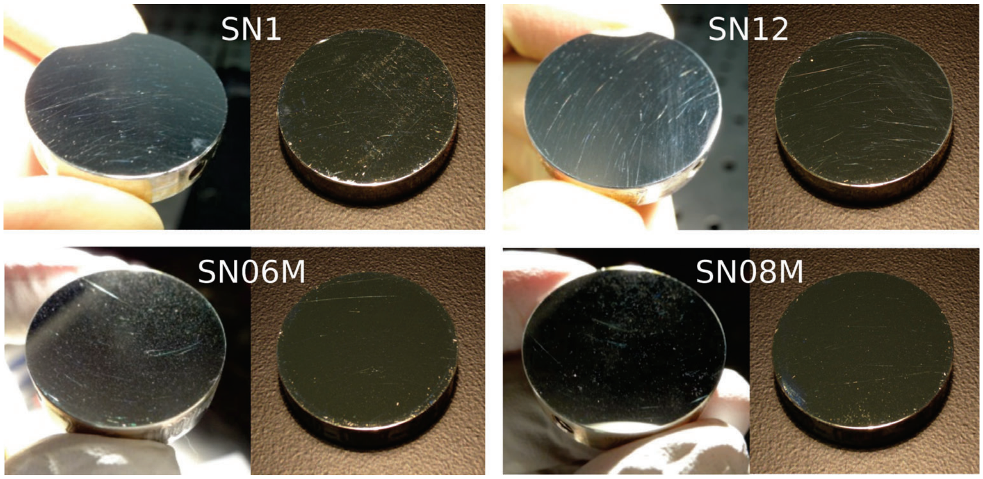

Figure 3. Couples of photographs of each sample immediately after coating (left), and after the storage period (right). Note that the orientation of the sample is not consistent in each couple.

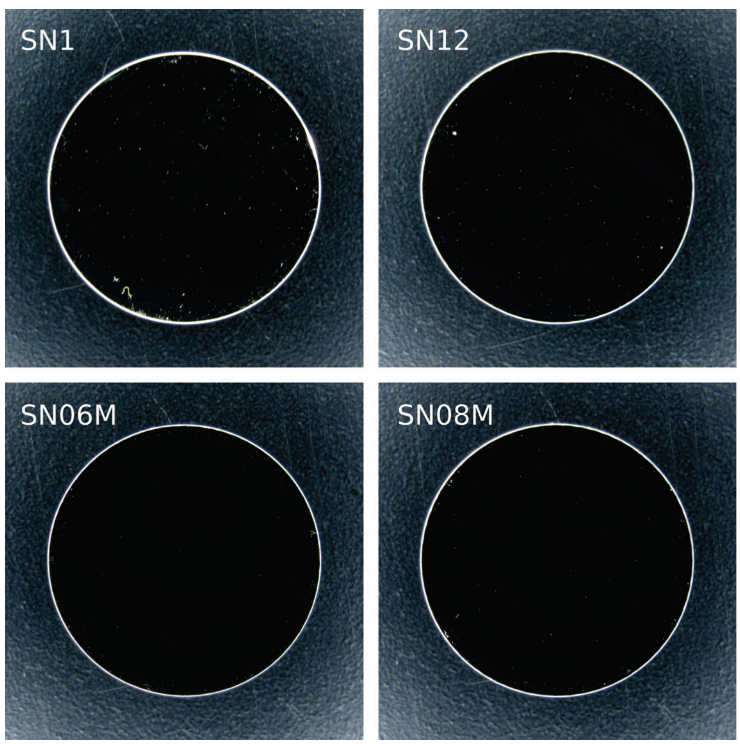

Figure 4. Darkfield photographs of the four samples after the storage period. Orientation of the samples is consistent with each right image of Figure 3.

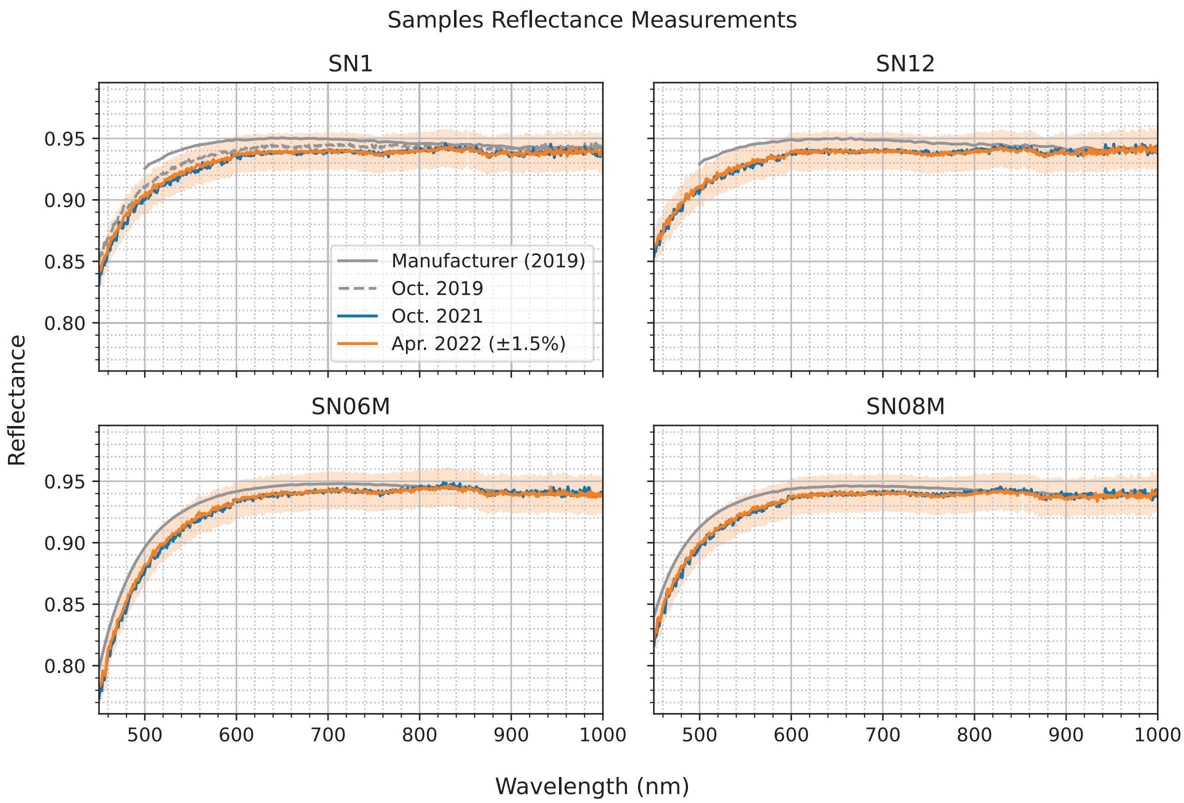

Figure 5. Reflectance measurements of four coated samples performed with two different setups, by the manufacturer and by the authors. One comparison measurement of sample SN1 (dashed gray line) was performed sufficiently close in time to the manufacturer's measurement to be useful to assess the cross-calibration of the two setups, which appear to have a bias.

4.2 Reflectance Measurements

Figure 5 shows the results of the reflectance measurements performed on the samples at different points in time. Samples reflectance was measured after coating and after qualification tests by the manufacturer (solid gray line), who found no degradation in performance.[6] One of the samples (SN01) was also measured by the authors early on during the qualification campaign, so this measurement could be used as reference for the cross-calibration of the two setups (dashed gray line).

Eventually two comprehensive measurement campaigns could be performed six months apart (in October 2021 and April 2022, orange and blue lines in the plots).

Considering the difference between the initial measurement of the in-house setup and the manufacturer's setup, and noting the estimated repeatability error, the results do not highlight a significant change in reflectance of the samples.

More precise measurements may be performed in the future to further confirm this preliminary result.

4.3 Atomic Force Microscopy

Two sets of AFM scans of representative areas of samples SN01 and SN06M are presented in Figures 6 and 7. For each set, the first scan (on top) was performed at the beginning of the storage period, after the sample underwent the qualification tests, and the second one (at the bottom), in August 2022.

As discussed in Section 3.3, the scans were performed to provide a qualitative assessment of surface morphology variations and to measure surface roughness. Since the time in storage did not produce any visible signs of surface degradation nor delamination, the sampling location for the AFM was chosen to be reasonably representative of the central area, where reflectance was also measured, without aiming at specific surface blemishes or scratches. Please also note that measurements of the same sample do not image the exact same portion of surface.

A comparison of the AFM images does not indicate the appearance of new topological structures of relevance: most features are attributable to scratches and dents that were equally present before storage. The white areas in relief on SN01 are likely the residues of tape adhesive from the adhesion tests. These were in fact visible upon careful examination of the surface area affected by the test. Anecdotally, AFM scans of sample SN01 did result in frequent tip pollution that required replacement, possibly because of the residues.

RMS roughness measurements also do not appear to change significantly before and after the cycles.

5. CONCLUSIONS AND NEXT STEPS

In the framework of the coating qualification program for the mirrors of the Ariel mission telescope, a series of samples of the mirrors substrate material, Al6061-T651, were tested and are currently being kept in storage and re-examined periodically for signs of degradation.

After three years, results of visual inspections (both with direct and darkfield illumination) and reflectance measurements showed no alteration in appearance imputable to deterioration or delamination of the coating, nor a significant degradation in optical performance in the waveband 400 nm to 1000 nm, according to preliminary measurements. Additional AFM scans of the samples showed no qualitative morphology variations nor an increase in surface roughness.

Further testing will be repeated in the future to confirm coating stability under cleanroom environmental conditions, equivalent or worse to those foreseen for Ariel telescope mirrors. Additional operational environment tests are also planned for the near future, in particular radiation testing with an ion bombardment program simulating Ariel L2 operating orbital environment.

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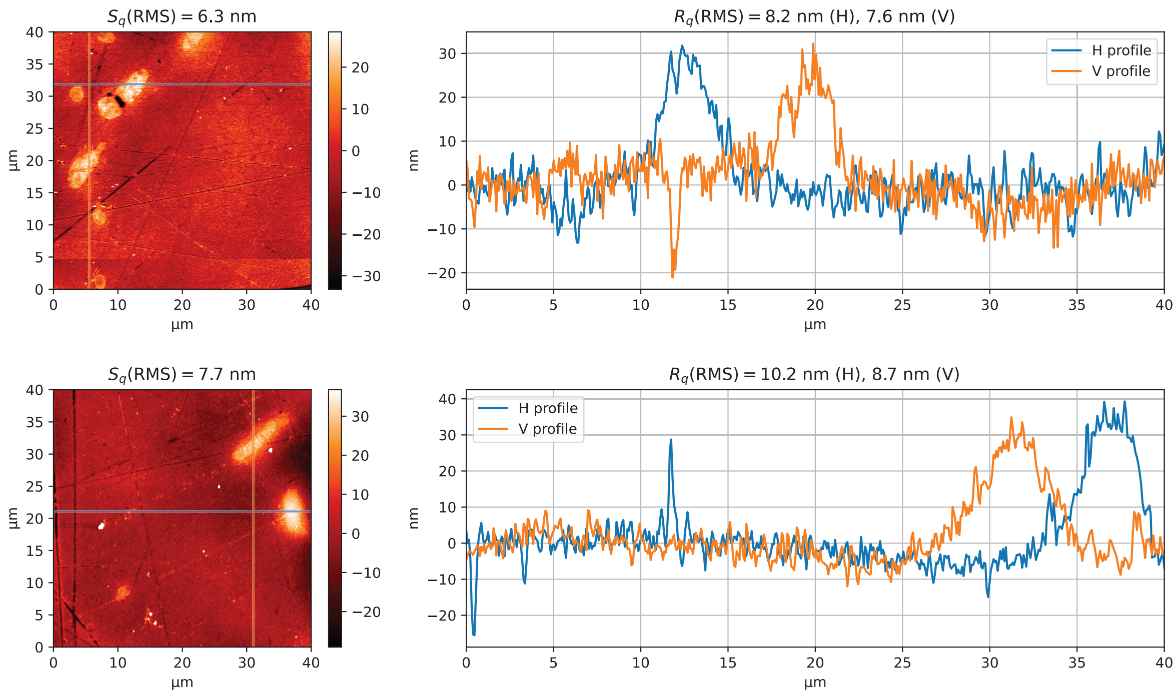

Figure 6. AFM scans (left) of sample SN01 before (top) and after (bottom) the storage period. For each scan, two orthogonal line profiles are also provided (plots on the right). The two scanned areas do not necessarily coincide.

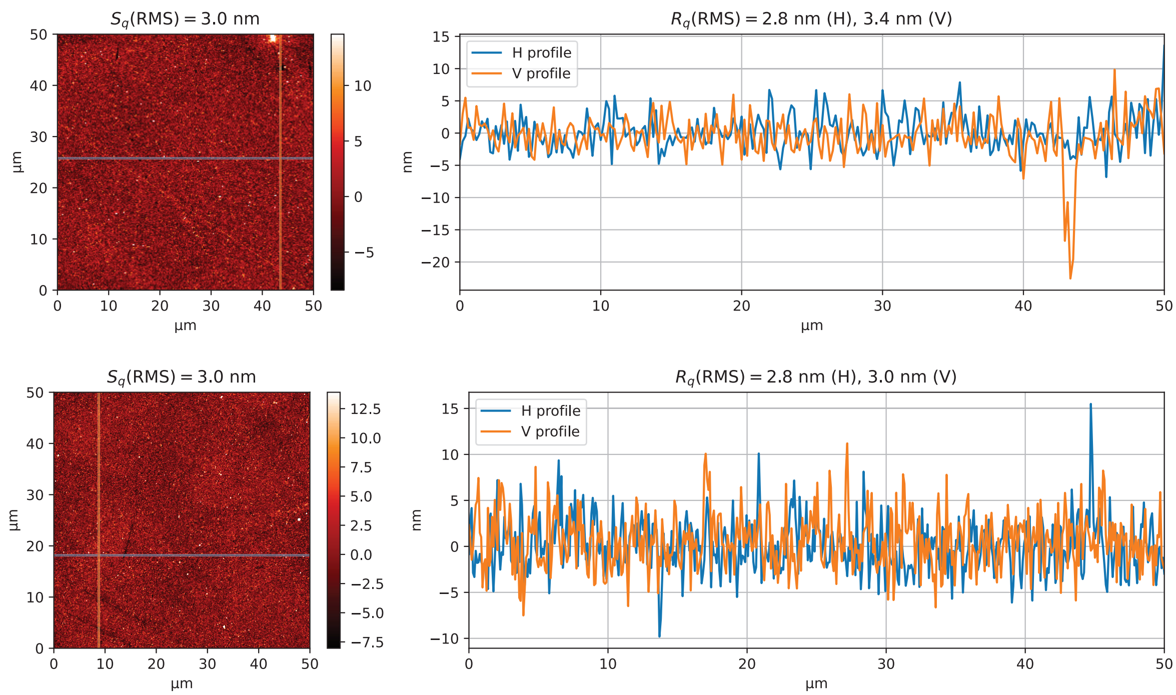

Figure 7. AFM scans (left) of sample SN06M before (top) and after (bottom) the storage period. For each scan, two line profiles are also provided (plots on the right). The two scanned areas do not necessarily coincide.

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