Research and development of VUV optical coatings for micro mirror applications

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Abstract: This paper deals with vacuum UV optical coatings for micro mirror applications. High reflecting low-stress optical coatings have been developed for the next generation of micro mechanical mirrors. The optimized metal systems are applicable in the VUV spectral region and can be integrated in the technology of MOEMS, such as spatial light modulators (SLM) and micro scanning mirrors.

Key words: vacuum UV; thin film; micro mirror; spatial light modulator

1 Introduction

During the last three decades, the development of powerful UV light sources such as excimer lasers, frequency multiplied solid state lasers or storage free electron lasers have gathered increasing research efforts in the fields of UV photon interaction with matter as well as rising industrial applications such as integrated circuit manufacturing, micro and nanomaterial processing or medicine. A dominant driving force down to the shortest wavelengths in the vacuum ultraviolet (VUV) spectral region is the semiconductor manufacturing with the optical lithography as key technologies for the generation of smaller lateral dimensions down to 100 nm and below. Emergent research and development fields such VUV micro mirror arrays for maskless lithography tools call for new requirements for MOEMS compatible materials, etchable and structurable designs. In that case, high reflecting low-stress optical coatings for the next generation of micro mechanical mirrors are required for applications, furthermore, these optical coatings should be integrated in the technology of MOEMS, such as spatial light modulators (SLM) and micro scanning mirrors. Therefore, it is a new challenge for optical thin film community to produce these optical coatings, which can meet the optical, mechanical and electrical properties in parallel.

2 Thin film materials and coating strategy

Principally, there are two kinds of possibilities to achieve highly reflective mirror coatings. The first is dielectric multilayer mirrors consisting of an alternating (LH)\textsuperscript{n} Bragg stack of low (L) and high (H) refracting, not absorbing dielectric materials, where each single layer of the Bragg stack usually has a thickness \( d \) of a quarter wavelength \( d = n \times 1/\lambda \) (\( n \) is the refractive index), and the other solution is metallic mir-
rors of a single or protected highly reflective dielectric layer.

Due to its unrivaled position of large bandgap, fluoride materials are the most favorable material for use in VUV region\(^7\). However, some oxides, such as Al$_2$O$_3$ and SiO$_2$ can also be employed as transparent dielectric materials in this band. When Al$_2$O$_3$ and SiO$_2$ are taken here as example for high reflecting pairs at 193 nm, calculations and test coatings have showed that metal systems enable high reflectivity (\(90\%\)) with relatively thin coating layers (50\(\mu\)m to 100 nm) compared to multilayer systems (up to 1\(\mu\)m thick for 90% reflectivity at 193 nm). As far as deformation and mechanical load are potential issues for micro mirror devices, thin metal solutions have been sought and developed, because they enable even highly reflective coatings with much lower thickness and consequently with a lower risk of stress induced mirror deformation. Metal materials can provide high reflectance with thin thickness, thus they are preferred as mirror technology, rather than the thick dielectric stacks.

3 VUV optical coatings deposition

The most important factor for producing aluminum films with the highest reflectance has been found to be extremely fast evaporation. The pressure during the deposition should be low, preferably not more than 1 \(\times\) 10\(^{-4}\) Pa; the aluminum should be of the highest purity and the substrate temperature should not be higher than about 100 °C\(^\circ\)\(^9\).\footnote{To improve the deposition, other techniques such as magnetron sputtering, electron beam evaporation, and direct current sputtering are also used.}

Aluminum layers were deposited by thermal evaporation. This thermal evaporation process was performed in a cryopumped Blazers BA K 640 batch coater, dielectric-capping layer on the aluminum was also thermally evaporated in BA K coater. As described above, fluorides as MgF$_2$, AlF$_3$ and LaF$_3$, oxides as SiO$_2$ and Al$_2$O$_3$ were selected as capping layer materials. Just after the evaporation of aluminum, dielectric-capping layer was in situ evaporated without vacuum break. Besides single capping layer strategy, MgF$_2$/LaF$_3$, SiO$_2$/Al$_2$O$_3$ multilayer capping layers were employed to enhance the reflectance at the intended wavelength. Furthermore, hybrid multilayer capping, i.e. MgF$_2$/SiO$_2$ and AlF$_3$/SiO$_2$ multilayer capping layers were also deposited to achieve maximum reflectance. Usually, LaF$_3$ and AlF$_3$ are deposited by thermal boat evaporation, whereas MgF$_2$ and oxide materials (Al$_2$O$_3$ and SiO$_2$) by electron beam evaporation. 99.99% purity materials are used. The coating and substrate cleaning were carried out under class 353, 357-35. 3357 (particles/\(\text{m}^3\)) clean room conditions.

4 VUV optical coatings characterisation

As for VUV optical coatings characterization, a customized VUV spectrophotometer has been developed at the Fraunhofer IOF based on a system of Laser Zentrum Hannover. The system is completely computer controlled, including automatic procedures for the photomultiplier (PM) positioning during the transmission and reflection measurements. A F$_2$-excimer laser has been coupled into the measurement chamber, which permits a sample irradiation prior to the measurement. The modified sample holder includes a goniometric bench, to enable measurements of reflectance \(R\) and \(I\) or the transmittance \(T\) at fixed angle over a given spectral wavelength range (115\(\mu\)m to 230 nm with 0.1 nm spectral resolution) or \(R\) or \(I\) and \(T\) angle resolved measurements at fixed wavelength from 0° to 85° (0.2° angle resolution). By using a Rochon prism of MgF$_2$ as a UV polarizer, first tests were started to obtain polarization resolved VUV data of \(R\), \(R_0\), \(T\), and \(T_p\)\(^{10}\)\footnote{The polarization resolved data can also be used to determine the degree of polarization and the polarization properties of the optical materials.}.\tableofcontents
Fig. 1 VUV photometry-example of angle-polarization resolved measurement at 193 nm (10°/20° incidence, s/p polarization $\lambda = 193$ nm)

Fig. 2 Enhanced aluminum system for 157 nm and 193 nm

Fig. 3 Enhanced aluminum coatings with fluoride capping

5 Results and applications

Researches and developments of high reflection coatings on micro mirror arrays have been carried out. Concerning dielectric multilayers, oxides and fluoride materials are analyzed to test CMOS compatibility and accumulated stresses and extract optical and physical characteristics.

For the VUV region, metal systems have been developed by various technologies such as thermal evaporation and magnetron sputtering, with proactive capping layers. Reflectivity above 91% is achieved at 193 nm and reflectivity around 90% is reached at 157 nm with thin and low stress aluminum enhanced reflection systems. As shown in Fig. 2, a broadband high reflectivity is available till 150 nm with smooth optical surface properties, which is of great interest for both VUV applications.

Thin films of AlF$_3$ or MgF$_2$ evaporated at low substrate temperatures immediately in the same vacuum cycle on top of a fresh thin quick deposited Al can maintain more than 90% reflectivity down to 157 nm. The thin fluoride layer protects the Al from extensive oxidation, and hence from a drop of reflectance at short wavelengths. Typically, for a protected aluminum reflector deposited under high vacuum conditions ($2 \times 10^{-5}$ Pa) and with a high evaporation rate of about 30 nm/s a reflectance of 91% at 193 nm and 90% at 157 nm is achievable.

Since highly reflecting aluminum layer can only be achieved at low temperature environment, the fluoride layers deposited with thermal evaporation technology under this environment will be columnar structure with numerous pores. In this case, it is very sensitive to air exposure and light irradiation. Besides fluoride materials, oxides materials are also employed to protect freshly deposited aluminum layer from oxidation. SiO$_2$ and Al$_2$O$_3$ are suitable candidates for the VUV optical coating applications.
as capping layer at wavelength above 190 nm, such as 193 nm lithography application. Nevertheless SiO₂ is a potential oxide capping material for the VUV spectral region. The deposition results show that it can maintain high reflectance till 175 nm.

In conclusion, Tab. 1 collects the reflectance, which have been realized based on different capping materials and different technologies. Generally around 90% reflectance can be achieved with fluoride and oxides as capping materials, while mirrors with oxide capping layers show robust environmental stability than fluoride capping layers. However, as for high reflecting optical coatings for 157 nm wavelength, only fluoride materials can be employed as capping and protection layers.

<table>
<thead>
<tr>
<th>Coating system</th>
<th>Deposition technique</th>
<th>Reflectance R in % @λ = 193 nm (DUV)</th>
<th>Reflectance R in % @λ = 157 nm (VUV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al-alloy</td>
<td>DC-magnetron sputter</td>
<td>75.80</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>Evaporation</td>
<td>88</td>
<td>73.4</td>
</tr>
<tr>
<td>Al/AlF₃</td>
<td>Evaporation</td>
<td>88</td>
<td>71</td>
</tr>
<tr>
<td>Al/MgF₃</td>
<td>Evaporation</td>
<td>90.9</td>
<td>89</td>
</tr>
<tr>
<td>Al/LaF₃</td>
<td>Evaporation</td>
<td>91.6</td>
<td>88</td>
</tr>
<tr>
<td>Al/Al₂O₃</td>
<td>Evaporation</td>
<td>84</td>
<td>88.4</td>
</tr>
<tr>
<td>Al/SiO₂</td>
<td>Evaporation</td>
<td>90.8</td>
<td>-</td>
</tr>
</tbody>
</table>

The developed VUV/DUV coatings are compatible with the requirements related to the CMOS technology of micro mirror arrays. These have been tested in various experiments concerning the process integration of highly reflective VUV coatings into the SLM fabrication process. The developed designs allow a convenient pattern transfer by optimized RIE techniques, withstand during SLM-fabrication aggressive plasma treatments with negligible degradation of their optical performance and enable induced stress control in order to guarantee the required high surface flatness and a defect minimized structure.

Fig. 4 shows an image of a structured micro mirror array with HR coating having a Al₂O₃ capping layer. The high surface flatness of a HR-DUV coated micro mirror test structure (mirror plate of 16μm × 16μm with central support post) is illustrated in Fig. 5 Mirror planarity of down to σₘₘ = 3.05 nm (averaged over 35 single mirrors) have been measured by means of a white light interferometer. At that level, HR coating systems for 248 nm, 193 nm and 157 nm have been developed as prototypes.

![Optical image of patterned SLM test structures with HR-enhanced Al coating and Al₂O₃ capping layer.](image-url)
systems. For that micro mirror test structures with HR-DUV coatings were illuminated using an excimer laser at 193 nm with a pulse dose at scale of $E_{\text{pulse}} = 100 \mu J/cm^2$ over $10^7$ pulses of 20 ns pulse length. In Fig. 6 the planarity of micro mirror test structures, occurring after high energetic DUV irradiation, is illustrated for SLM test samples with HR-DUV coating of enhanced aluminum in comparison to reference samples of conventional design without HR-coating.

Whereas the reference samples of conventional design, consisting of a single aluminum alloy layer without an additional optical coating, have shown a large mirror degradation during the DUV irradiation test at 193 nm (Fig. 6(a)), no degrease of mirror planarity occurs for the SLM test samples with HR-DUV coating of enhanced aluminum (Fig. 6(b)). Even after the harsh DUV irradiation test the SLM-samples with HR-DUV coating show an excellent mirror planarity of $\sigma_{\text{rms}} = 2.84$ nm (for comparison the initial planarity was $\sigma_{\text{rms}} = 3.05$ nm before DUV-irradiation test). Consequently the DUV/VUV long term stability and laser damage threshold of micro mirror arrays can clearly improved by introducing a highly reflective enhanced aluminum coating into the mirror design.

6 Conclusions and outlook

Highly reflective low-stress optical coatings for the next-generation of micro mechanical mirrors have been developed for MOEMS applications in the VUV spectral region. The enhanced aluminum systems are applicable for the VUV spectral region and can be integrated in the technology of MOEMS, such as spatial light modulators (SLM) and micro scanning mirrors. The developed designs reconcile high reflectivity and an improved laser damage threshold without compromising the micro mirror planarity.

By means of aluminum with thin, low-
stress, and protective systems, high reflectivity around 90% has been reached over an extended wavelength region starting from 200 nm and going down to 150 nm. These developed VUV coatings are compatible with the requirements related to the CMOS technology of micro mirror arrays. The developed designs allow a convenient pattern transfer by RIE techniques, withstand during SLM-fabrication aggressive plasma treatments with negligible degradation of their optical performance and enable induced stress control in order to guarantee the required high surface flatness. SLMs with enhanced aluminum coatings show an excellent long-term stability of surface flatness and an improved laser damage threshold, which have been tested in a harsh irradiation test at 193 nm.

The aluminum with protection or enhancement dielectric layers system at 193 nm have matured for application, further investigations will concentrate on other laser wavelengths such as 157 nm, 308 nm and 1064 nm applications.

7 Acknowledgements

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References:


Brief professional biography of the author:

Dr. Minghong Yang received his Ph. D. degree from Huazhong University of Science and Technology, Wuhan, China in 2003. Since 2004, he is a visiting scientist at the Fraunhofer Institute of Applied Optics and Precision Engineering. His research interest focuses on optical thin film design, manufacturing and characterization, especially for the Vacuum UV spectral region.