Article ID 1004-924X(2005)04-0465-06

Research and development of VUV optical coatings for micro mirror applications

Ming-hong Yang, Alexandre Gatto, Norbert Kaiser

(Fraunhofer IOF, Albert-Einstein-Str. 7, D-07745 Jena, Germany)

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 nano-material 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[1-3]. 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[4-6]. 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 $(LH)^N$-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 $d = n \times 1/4\lambda$ (n is the refractive index), and the other solution is metallic mir-

Received date: 2005-06-06; **Revised date:** 2005-06-16.

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

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_2O_3 and SiO_2 can also be employed as transparent dielectric materials in this band. When Al_2O_3 and SiO_2 are took 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 (50~100 nm) compared to multilayer systems (up to 1 μm 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 1×10^{-4} Pa; the aluminum should be of the highest purity and the substrate temperature should not be higher than about 100 ℃[8-9].

Aluminum layers were deposited by thermal evaporation. This thermal evaporation process was performed in a cryo-pumped Blazers BAK 640 batch coater, dielectric-capping layer on the aluminum was also thermally evaporated in BAK coater. As described above, fluorides as MgF_2, AlF_3 and LaF_3, oxides as SiO_2 and Al_2O_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_2O_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_2O_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/m^3) clean room conditions.

4 VUV optical coatings charaterisation

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 / or the transmittance T at fixed angle over a given spectral wavelength range (115~230 nm with 0.1 nm spectral resolution) or R or / 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_s, R_p, T_s and T_p[10].

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

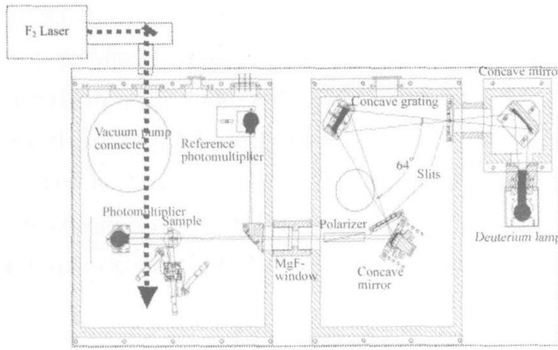


Fig. 1 VUV photometry-example of angle-polarization resolved measurement at 193 nm (10~20° incidence, s/p polarization $\lambda = 193$ nm)

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 (2×10^{-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.

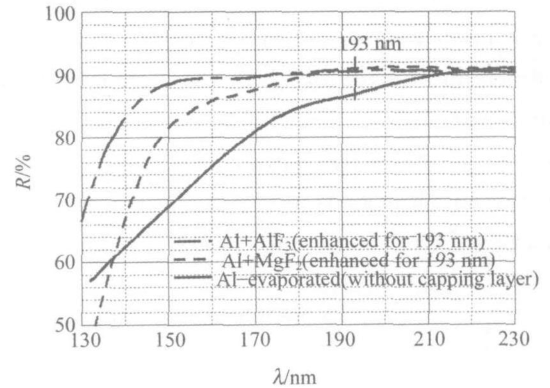


Fig. 2 Enhanced aluminum system for 157 nm and 193 nm

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[11]. In this case, it is very sensitive to air exposure and light irradiation[12]. Besides fluoride materials, oxides materials are also employed to protect freshly deposited aluminum layer from oxidation. SiO_2 and Al_2O_3 are suitable candidates for the VUV optical coating applications.

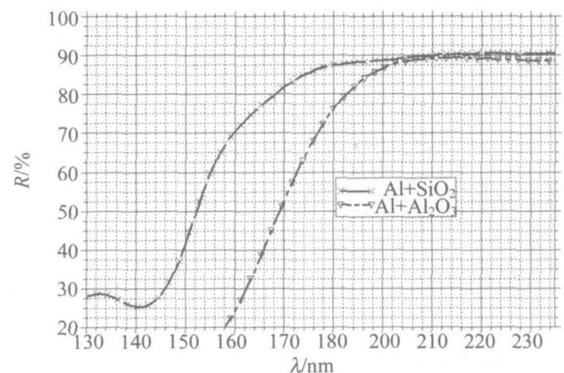


Fig. 3 Enhanced aluminum coatings with fluoride capping

Fig. 3 depicts the achieved reflectance with optimized oxides material thickness. It is clear that reflectance with Al_2O_3 as protection layer drops dramatically from 190 nm to lower wavelength, however this materials still can be used

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

as capping layer at wavelength above 190 nm, such as 193 nm lithography application. Nevertheless SiO_2 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.

Tab. 1 Reflectance of enhanced aluminum coatings deposited on Si-substrate

Coating system	Deposition technique	Reflectance R in % @λ = 193 nm (DUV)	Reflectance R in % @λ = 157 nm (VUV)
Al-alloy	DC-magnetron sputtern	75-80	-
Al	Evaporation	88	73.4
Al	DC-magnetron sputtern	88	71
Al/AlF_3	Evaporation	90.9	89
Al/MgF_2	Evaporation	91.6	88
Al/LaF_3	Evaporation	84	88.4
Al/Al_2O_3	Evaporation	90.8	-
Al/SiO_2	Evaporation	89.2	60

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 Al_2O_3 capping layer. The high surface flatness of a HR-DUV coated micro mirror test structure (mirror plate of 16 μm $\times$16 μm with central support post) is illustrated in Fig. 5 Mirror planarity of down to σ_{rms} = 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.

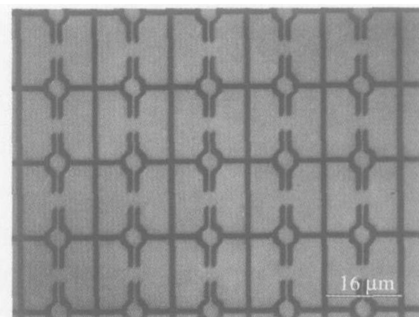


Fig. 4 Optical image of patterned SLM test structures with HR-enhanced Al coating and Al_2O_3 capping layer.

SLM's with enhanced aluminum coatings show an improved VUV damage threshold and an excellent long-term stability of surface flatness even during highly energetic VUV radiation. This have been tested in a harsh irradiation test at λ= 193 nm with much higher laser power densities than used by direct writing lithography

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

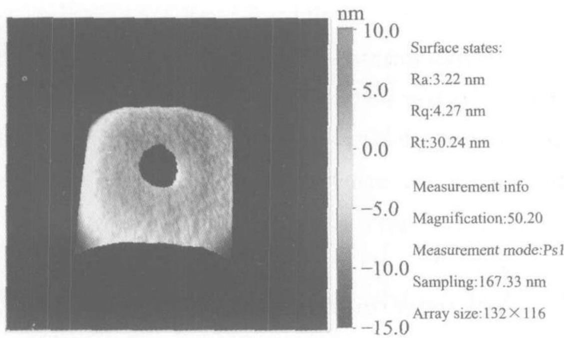
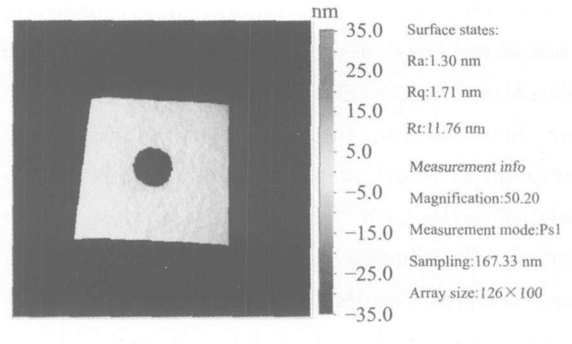


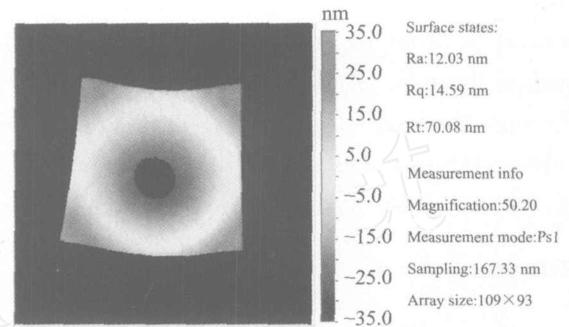
Fig. 5 Planarity of a 16 μm ×16 μm micro mirror test structure with HR-DUV enhanced Al coating, measured by means of a white light interferometer.

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 $E_{pulse} = 100\ \mu J/cm^2$ 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 ($\sigma_{rms} = 2.84$ nm (for comparison the initial planarity was $\sigma_{rms} = 3.05$ 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.



(a)



(b)

Fig. 6 Planarity of 16 μm ×16 μm micro mirror test structures with/without HR-DUV coating after DUV irradiation test ($\lambda = 193$ nm, $E_{pulse} = 100\ \mu J/cm^2$, 10^7 pulses), mirror flatness measured by white light interferometry.
(a) SLM with HR-DUV coating of enhanced aluminum, (b) reference sample of Al alloy without HR optical coating.

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-

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net

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. SLM's 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

The presented results have been developed in a joint project (economic based strategic alliance ("WISA") called "Next Generation Micro Mechanical Mirrors" of four German Fraunhofer institutes (IPMS, IOF, IWS, IZFP). The financial support of Fraunhofer Society is greatly acknowledged.

References:

[1] M. Rothschild, A. R. Forte, R. R. Kunz, S. C. Palmateer, J. H. C. Sedlacek. Lithography at a wavelength of 193 nm [J]. *IBM J. Res. Develop*, 1997, 41: 49-54.

[2] M. Rothschild. Photolithography below 200 nm[J]. *SPIE*, 1998, 3274: 222-225.

[3] M. Rothschild, T. M. Bloomstein, J. E. Curtin, *et al*. 157 nm: Deepest deep-ultaviolet yet[J]. *J. Vac. Sci., Technol.*, 1999, B17: 3262-3266.

[4] U. Ljungblad, U. Dauderstädt, P. Dürr, *et al*. New laser pattern generator for DUV using spatial light modulator [J]. *Microelectronic Engineering*, 2001, 57-58: 23-29.

[5] T. Sandström, U. B. Ljungblad, P. Dürr, *et al*. High-performance laser pattern generation using spatial light modulators (SLM) and deep-UV radiation[J]. *SPIE*, 2001, 4343: 35.

[6] D. Dudley, W. Duncan, J. Slaughter. Emerging digital micromirror device (DMD) applications[J]. *SPIE*, 2003, 4985: 14-25.

[7] R. Thielsch. Optical coatings for the DUV/VUV (Ads.) [J]. *Springer Series in Optical Sciences*, 2003, 88: 257-279.

[8] E. T. Hutcheston, G. Hass, J. T. Cox. Effect of deposition rate and substrate temperature on the vacuum ultraviolet reflectance of MgF_2- and LiF- overcoated aluminium mirrors[J]. *Appl. Opt.*, 1972, 11: 2245-2248.

[9] HASS G. Reflectance and preparation of front-surface mirrors for use at various angles of incidence from the ultraviolet to the far infrared[J]. *J. Opt. Soc. Am.*, 1982, 72: 27-39.

[10] J. Heber, A. Gatto, N. Kaiser. Spectrophotometer in the vacuum UV[J]. *SPIE*, 2002, 4932: 544-548.

[11] H. Günther. Structure and related properties of thin-film optical coatings[J]. *SPIE*, 1986, 678: 2-11.

[12] A. Gatto, R. Thielsch, J. Heber, N. Kaise, *et al*. High-performance deep-ultraviolet optics for free electron lasers[J]. *Appl. Opt.*, 2002, 41: 3236-3241.

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.

© 1994-2010 China Academic Journal Electronic Publishing House. All rights reserved. http://www.cnki.net