Surface & Coatings Technology 311 (2017) 351–356

Contents lists available at ScienceDirect

Surface & Coatings Technology

journal homepage: www.elsevier.com/locate/surfcoat

Effect of ion beam etching on the surface roughness of bare and silicon covered beryllium films

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ARTICLE INFO

Article history:
Received 5 September 2016
Revised 13 December 2016
Accepted in revised form 8 January 2017
Available online 10 January 2017

Keywords:
X-ray (EUV) mirrors
Ion polishing
Roughness
Beryllium

ABSTRACT

Due to low density, high mechanical rigidity and thermal conductivity, ease of machining beryllium is one of the most promising materials for space mirrors, including for studies of the solar corona in the wavelength range of 13–30.4 nm. An obstacle to the widespread use of this material is its large surface roughness after mechanical polishing. In this paper, using samples of 200 nm thick beryllium films deposited on silicon substrates and polished bulk beryllium, we studied the main aspects of using ion-beam etching for finish polishing of beryllium. We present the results of investigation pertaining to the influence of the neon ion energy and angle of incidence on the beryllium films surface roughness. We measured the etching rates depending on the angle of incidence and energy of neon ions. We found that 400 eV is the optimal energy for neon ion etching ensuring slight surface roughness smoothing in the range of incidence angles of ±40°. The deposition of 200 nm amorphous silicon films onto beryllium and their subsequent etching with the 800 eV argon ions improve the effective surface roughness integrated across the range of the spatial frequencies of 0.025–60 μm^{-1}, from $\sigma_{eff} = 1.37$ nm down to $\sigma_{eff} = 0.29$ nm. The effectiveness of the smoothing technology for X-ray applications has been confirmed by the results of the study of the reflective properties of the Mo/Si mirrors deposited on the substrate. The reflectivity at a wavelength of 13.5 nm increased from 2% for the substrates with the surface roughness of $\sigma_{eff} = 2.3$ nm (the roughness value corresponds to the as-prepared bulk Be substrates and is taken from the literature) up to 67.5% after the smoothing technology.

1. Introduction

In connection with the advent of newer, more powerful sources of soft X-ray and extreme ultraviolet radiation (undulators, free-electron lasers, laser-plasma sources, etc.) there raised a problem of radiation-resistant or well heat-removing mirrors. Especially this is a challenging problem for mirrors with multilayer interference coatings because the radiation-induced heating of multilayer mirrors (MLM) not only leads to deterioration of imaging properties but might also cause degradation of reflectance of the mirrors due to crystallization, mixing and oxidation of layers.

One possible strategy to overcome this negative factor is associated with the search for the composition of the heat-resistant MLM. In the case of collectors of Zerodur (a registered trademark of Schott AG, is a lithium-aluminosilicate glass-ceramic) or SiC substrates for EUV (extreme ultraviolet) lithography researchers looked for an alternative to Mo/Si MLM. In [1] they studied the MoSi2/Si and Mo/C/Si/CMLMs. The temperature of annealing reached 500 °C during 100 h. The first structure has demonstrated sustained reflection on a level of 41.2%. For comparison, the theoretical limit of the Mo/Si MLM reflectance is over 73% and the experimental values are around 70%. Annealing mirrors with carbon barrier-layers results in a monotonic decrease of the reflectance. A more successful solution with "secret" barrier layers, Mo/X/Si/X MLM, was reported in [2]. The maximum reflectance of the thermo-stable mirror was about 60%.

However, the resulting reflectance is substantially <70% achieved with conventional Mo/Si MLM. The obvious solution of this problem is to use substrate materials for MLM with high thermal conductivity; in particular, metals. In [3] was reported a rather high reflectance (60% at a wavelength of 0.154 nm) of Ni/C MLM deposited onto a copper substrate covered with 50 μm electrochemical nickel coating. One of the contemporary works we would like to specifically note [4], where the Mo/Si MLM for a EUV collector was deposited onto a water-cooled substrate made of aluminum and nickel. Reflectance of unpolarized

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http://dx.doi.org/10.1016/j.surfcoat.2017.01.023

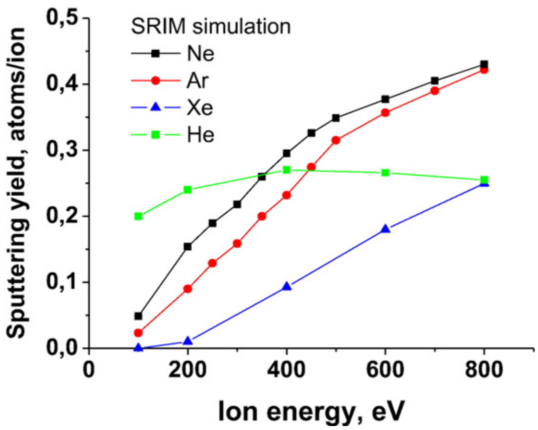

Fig. 1. The sputtering coefficient of Be by ions of inert gases: He, Ne, Ar and Xe. The calculation was done with the SRIM software [23].

radiation at a wavelength of 13.5 nm varied from 42 to 58% depending on the angle of incidence. Maximum reflection corresponded to an angle of 5° from normal. It should be noted that in both cases because of large-scale metal substrates microroughness the reflection coefficients are significantly less than in theory.

An even more serious problem arises in the design of telescopes to study the solar corona in the extreme ultraviolet range. At present, both in Russia and in the United States space missions are being organized in which satellites will be in orbit close to Mercury [5,6]. In this case, the thermal load on the optical elements is increased up to 2.3 W/cm^2, and to reduce the MLM temperature to an acceptable level (typically not >100 °C) a well heat conductive substrate is required.

As a substrate material for the application mentioned above, beryllium is of considerable interest because it combines good thermal characteristics (temperature coefficient of linear expansion $\alpha \approx 10^{-5}$ K^{-1}, less than copper and aluminum, coefficient of thermal conductivity $\gamma \approx 200$ W/(m × K) close to Al and only two times worse than Cu) with a low weight density $\rho = 1.85 \times 10^3$ kg/m^3 (nearly 1.5 times less than Al and 5 times less than Cu).

The substrates for MLM are characterized by the highest requirements for their micro-roughness. To provide high (close to the theoretical limit) reflectivity of multilayer mirrors of the EUV wavelength range, in particular at a wavelength of 13.5 nm, the roughness of the substrate surface is necessary to be at a level 0.3–0.5 nm [7]. And, while for SiC (material with not a poor thermal conductivity of $\gamma \approx 31$ W/(m × K) and relatively low density $\rho = 3.21 \times 10^3$ kg/m^3), there is a wealth of information on the achieved roughness, for example, [8], the information on beryllium substrates is much poorer, and presented mostly on the websites of commercial companies. In particular, in [9], it is reported that "…since beryllium is a powdered metal, there are natural limits to the finish that can be achieved by directly polishing the metal. Hardric has polished several bare beryllium retroreflector panels 25 cm × 12.5 cm to 2 nm rms surface finish with a surface flatness of 1/20 wave at 633 nm P-V. In smaller mirrors even better surfaces can be achieved.

Nickel-plated beryllium mirror blanks are plated with 0.05 mm to 0.13 mm of electroless nickel in order to have a surface that can be either readily polished with conventional techniques or that can be diamond turned also are excellent for use in corrosive environments, when surface finishes must be better than 2 nm rms, or for diamond turning nonflat surfaces."

In [10] similar roughness parameters are reported to be obtained when polishing beryllium, and its relatively poor polishability is also noted.

One of the methods for the finish polishing of optical components is ion-beam etching. Its efficiency was demonstrated for a number of optical materials [11–14]. However, data on the etching rates as well as the influence of ion-beam etching on the surface roughness of beryllium are not available in the literature. Therefore, the main objectives of this study were as follows. Firstly, explore the dependence of the etching rates and the surface roughness on the ion energy and the angles of incidence onto the treated bare beryllium samples. Secondly, to find ways to radically improve the surface roughness. At this stage of studies as experimental samples we use the beryllium films deposited onto silicon substrates. Because all the basic physical and chemical properties of thin films of most metals, including beryllium, starting from the thicknesses of a few tens of nanometers, are practically identical to the properties of bulk materials, we consider such an approach appropriate. Later we plan to use the results of this investigation for testing ion polishing technology of beryllium substrates of bulk material in order to satisfy the roughness requirements for the substrates for X-ray applications, in particular the collector for lithographer at a wavelength of 13.5 nm and mirrors for orbital telescopes.

2. Sample preparation and experimental methods

As experimental samples we used 200 nm thick beryllium films deposited by magnetron sputtering onto the silicon substrates with a size of 15 × 15 mm. Initial microroughness of the silicon wafers measured in the spatial frequency range of 0.5–60 μm^{-1}, was about 0.1 nm, an effective surface roughness in the spectral range of 0.025–60 μm^{-1} was about 0.3 nm.

The ion-beam etching experiments were performed with the setup described in [15] with the use of a cold cathode technological ion gun. The ion energy varied in the range of 200–800 eV, the ion beam current was 30 mA. The installation was pumped by oil-free turbo-molecular and backing pumps, which provided a preliminary vacuum in the installation of 7 × 10^{-7} Torr. The working gas pressure during the etching process was 1 × 10^{-4} Torr.

The surface roughness measurements in the range of spatial frequencies of 0.025–60 μm^{-1} were performed with an atomic force

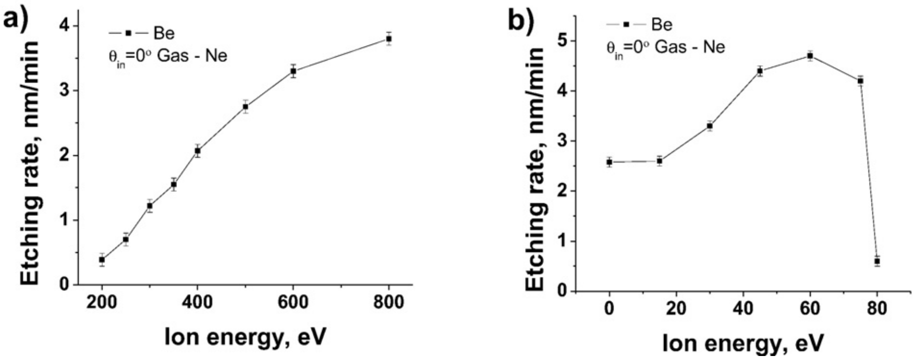

Fig. 2. Etching rate of Be film depending on the energy of Ne ions, $\theta_{in} = 0°$ – a), and on angle of incidence, $E_i = 400$ eV – b).