Optik 127 (2016) 588–592

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Design calculations and characterization of C/Cr multilayer mirrors in the 6 nm BEUV

Radhwan Alnaimi [a,c,*], Haixia Wang [b], Zhong Zhang [b], Xiaowei Yang [b], Mingwu Wen [b]

[a] Plasma Physics Group, Department of Physics, Imperial College London, London SW7 2AZ, UK
[b] Institute of Precision Optical Engineering, Tongji University, Shanghai 200092, China
[c] Department of Physics, King's College London, Strand, London WC2R 2LS, UK

ARTICLE INFO

Article history:
Received 9 January 2015
Accepted 25 October 2015

Keywords:
Multilayer
Design calculations
Characterization
Reflectance
Surface roughness

ABSTRACT

This paper focuses on the design, fabrication and characterization of the reflectivity and bandwidth of C/Cr multilayer mirrors of variable layer numbers (N = 30, 40, 100, 150 and 200) in order to exploit them as efficiently as possible at a wavelength of 6 nm. Magnetron sputtering technique was used with high base vacuum and high purity working gas (Argon 99.99%) together with a stable deposition rate during the fabrication process. The multilayers were probed using a hard X-ray diffraction method (Cu Kα radiation, λ = 0.154 nm) to characterize their reflectivity, bi-layers structure and surface roughness. An atomic force microscope was used to determine the surface topography and to analyze the surface structure imperfections such as roughness and stress induced damage. These were believed to occur during the preparation of the substrate or fabrication process. Various imperfections may also have developed due to oxidization after post production exposure to air. The surface roughness values obtained using X-ray scattering and atomic force microscopy were found to be in good agreement with each other.

1. Introduction

Multilayer mirrors play a significant role in the deployment of extreme ultraviolet lithography (EUVL) as a production and diagnostic tool in many applications including X-ray astronomy, X-ray focusing, and plasma diagnostics. One of the biggest challenges in EUVL has been to shorten the source wavelength and at the same time maintain the efficiency of the process [1]. The transition of the target wavelength from 13.5 nm to 6.5–6.9 nm, which lies beyond the EUV range, offers the possibility of very much needed, higher imaging resolution [2]. Short-wavelength radiation sources and high-reflectivity multilayer mirrors optimized for use near 6 nm will therefore be extremely useful to the semiconductor industry as they can dramatically increase the visibility of fine details during node inspections of microchip components. It is not possible to do this effectively with the current state of EUVL.

2. The design of multilayer mirrors

Prior to the mirror fabrication process, it is important to define the optimum structure of the multilayer's design and to understand the expected features of the key optical parameters, including reflectivity, transmittance and phase performance. The selection of suitable multilayer materials, based on optical constants and material stability, is the starting point of the design process [3]. The optimization of particular designs is complicated and can only be enabled using various computer algorithms.

2.1. *Computational method and background theory*

Computations of the design parameters such as reflectivity, transmittance, and absorptance are based on the Fresnel equations, modified to account for interface imperfections. The equations describe the reflection and transmission of an electromagnetic plane wave incident on an interface between two optically dissimilar materials (Fig. 1) [4]. In the case of an ideal reflection and transmission, the complex index of refraction $n = n + ik$ (where n is the refractive index and k is the extinction coefficient) is given for the two materials as n_a and n_b. The incident wave vector, with electric field amplitude E_a, makes an angle θ_a with respect to the interface normal along the z axis.

The amplitudes of the reflected, E'_a, and transmitted, E_b, electric fields are given by the Fresnel equations [5]. For s polarization (where E is defined to be perpendicular to the plane of incidence)

$$\frac{|E'_a|}{|E_a|} = \frac{n_a \cos\theta_a - n_b \cos\theta_b}{n_a \cos\theta_a + n_b \cos\theta_b} \equiv r^s_{ab} \quad (1)$$

* Corresponding author at: Plasma Physics Group, Department of Physics, Imperial College London, London SW7 2AZ, UK. Tel.: +44 7999064606.
E-mail address: r.alnaimi13@imperial.ac.uk (R. Alnaimi).

http://dx.doi.org/10.1016/j.ijleo.2015.10.118
0030-4026/

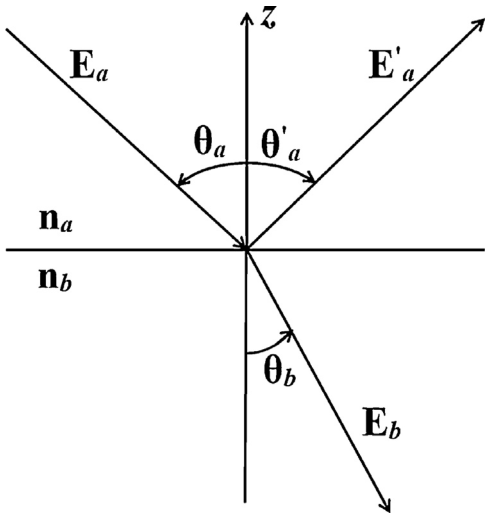

Fig. 1. Electric field components of a plane wave incident at the interface between two optically dissimilar materials of index n_a and n_b following [4].

and

$$\frac{|E_b|}{|E_a|} = \frac{2n_a\cos\theta_a}{n_a\cos\theta_a + n_b\cos\theta_b} \equiv t^s_{ab} \tag{2}$$

whereas, for p polarization (where E is parallel to the plane of incidence)

$$\frac{|E'_a|}{|E_a|} = \frac{n_a\cos\theta_b - n_b\cos\theta_a}{n_a\cos\theta_b + n_b\cos\theta_a} \equiv r^p_{ab} \tag{3}$$

and

$$\frac{|E_b|}{|E_a|} = \frac{2n_a\cos\theta_a}{n_a\cos\theta_b + n_b\cos\theta_a} \equiv t^p_{ab} \tag{4}$$

where r^s, t^s and r^p, r^p are the amplitude reflectance and transmittance for both s and p polarized wave vector respectively.

The angle, θ_b, is the angle of refraction is determined from Snell's law: $n_a\sin\theta_a = n_b\sin\theta_b$.

2.2. The role of interface imperfections

Interface imperfections, i.e., the interfacial roughness or a diffuse interface between two bi-layers give rise to losses in the specular reflectance. They also provide an indication of the expected interface profile function $p(z)$ between two layers. The non-abrupt change in the index of refraction across the interface can be described by a profile function $p(z)$ (see Fig. 2).

The function follows from the formalism developed by Stearns [4,6] defining the normalized average value $p(z)$ along the z direction of the dielectric function $\varepsilon(x)$ and $n = \sqrt{\varepsilon}$

$$p(z) = \int \frac{\int\int \varepsilon(x)dxdy}{(\varepsilon_a - \varepsilon_b)\int\int dxdy} \tag{5}$$

where

$$\varepsilon(x) = \begin{cases} \varepsilon_a, & Z \to +\infty \\ \varepsilon_b, & Z \to -\infty \end{cases} \tag{6}$$

In the case of non-abrupt interfaces, the resultant loss in specular reflectance can be approximated by multiplying the Fresnel reflection coefficients, Eqs. (1) and (3), by the function $\tilde{w}(s)$, which is the Fourier transform of $w(z) = dp/dz$. The modified Fresnel reflection coefficient is then given by

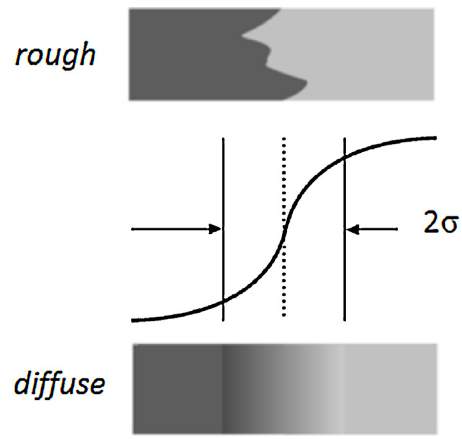

Fig. 2. A simplified description of the role of interfacial roughness or a diffuse interface between two bi-layers at an interface and its influence on the profile function $p(z)$.

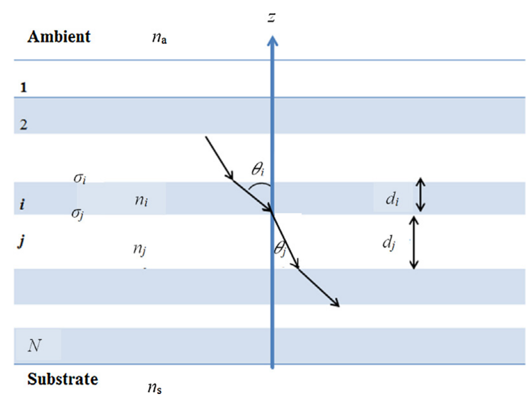

Fig. 3. A multilayer stack containing N layers, where the optical constants, thickness, propagation angle, and interface roughness/diffuseness parameter of the ith layer are n_i, d_i, θ_i, and σ_i, respectively. The ambient (i.e., the region above the film) has optical constants n_a, and the substrate has optical constants n_s [9].

$$r_{ij} = r_{ij}\tilde{w}(s_i) \tag{7}$$

where i and j denote the ith and jth layers consecutively.

2.3. Optical functions of a multilayer stack

A multilayer stack is a series of N layers (and $N+1$ interfaces) [4,7] where the ith layer has a thickness d_i, interfacial roughness/diffuse interface σ_i and optical constant n_i (Fig. 3). The region above the stack (ambient) has an optical constant n_a, and the region below (the base substrate) has an optical constant n_s. For a free-standing stack ($n_a = n_s$), the net reflection coefficient, r_i, of the ith layer is given by [7]

$$r_i = \frac{r_{ij} + r_j e^{2i\beta_i}}{1 + r_{ij}r_j e^{2i\beta_i}} \tag{8}$$

and the net transmission coefficient, t_i, of the ith layer is

$$t_i = \frac{t_{ij}t_j e^{2i\beta_i}}{1 + r_{ij}r_j e^{2i\beta_i}} \tag{9}$$

where

$$\beta_i = \frac{2\pi d_i n_i\cos\theta_i}{\lambda} \tag{10}$$

The amplitude reflection coefficient, r_{ij}, is computed from Eq. (7) and the transmission coefficient, t_{ij}, from Eqs. (2) and (4). The net reflection and transmission coefficients, t_j and r_j, refer to the jth interface.