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Robust design of broadband EUV multilayer using multi-objective evolutionary algorithm

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ABSTRACT

Considering the random fluctuations of the layer thickness, a method of robust design of broadband EUV multilayers based on multi-objective evolutionary algorithm is presented. Owing to the optimization of multi-objective evolutionary algorithm, the optical performance and robust quality of broadband Mo/Si multilayer can be optimized simultaneously, and then a set of robust designs of aperiodic EUV multilayers, which are insensitive to the thickness errors can be obtained in one single simulation run. The robust designs of broadband Mo/Si multilayers could be used to reduce the production risks of EUV mirrors, and this research demonstrates a great potential of application of multi-objective evolutionary algorithm on the design of optical thin film.

1. Introduction

In the last three decades, the multilayer mirrors have been used in the development of next generation of lithography system for the semiconductor industry [1–3], but due to the narrow spectral and angular bandwidth of standard periodic multilayer, the range of their applications is limited. In many applications such as EUV metrology, X-ray astronomy and X-ray ultrashort pulses [4–7], it is desirable that either the spectral or angular bandwidth is essentially increased [8–10]. The way generally used to increase the reflectivity bandwidth of periodic multilayer is the variations of layer thicknesses in the multilayer, and such coating is defined as aperiodic multilayer or supermirror. The theoretical approaches for the design of broadband multilayer are based either on full numerical calculations [11–17] or numerical calculation with an appropriate initial structure [18–22]; and suitable algorithms such as evolutionary strategy [11–15], stimulated annealing algorithm [16,17], Levenberg–Marquardt [18–22], and particle swarm optimization [23] have been used. Among these optimization algorithms, the algorithms of Levenberg–Marquardt and evolutionary strategy are widely used. It can be expected that better multilayer designs should be obtained when the thickness of each layer is considered as an independent variable. Under this consideration, the multilayer design spans a whole solution space in principle, and the better reflectivity performance can be found. However, due to the large amount of independent parameters, the Levenberg–Marquardt algorithm usually tends to get trapped in the local minima, and the achievement of globally optimum usually depends on the choice of initial multilayer structure [18–22]. By contrast, the evolutionary strategy such as genetic algorithm is a more suitable approach to the optimization of broadband multilayer when all the layer thicknesses are allowed to modulate, because this algorithm is a global optimization method, and a near-optimum solution can be found in an acceptable calculation time [11–15].

We realize that it is not very difficult to obtain a desirable thickness distribution with the algorithms above mentioned, and there are a number of different thickness distributions that can provide the similar reflectivity profile within a prescribed accuracy, but these multilayer designs give different performances when random thickness errors are considered. It is found that random thickness errors which originate from imprecision deposited control could lead to a deformation of the reflectivity curve [10,18]. Many researches have been carried out to consider the influences of random thickness errors on the optical performance in the optimization procedures, and a robust multilayer design whose optical performance is insensitive to the thickness errors can be obtained [24–26]. In the optimization procedure of traditional design, only the optical performance is the optimized objective, and optical performance of obtained multilayer design is usually sensitive to the random thickness errors. While in the optimization procedure of robust

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design, the robust quality is set as the optimized objective, but optical performance of obtained multilayer design usually cannot be acceptable. Therefore, we realize that the optical and robust performances of multilayer should be equally important in the fabrication, and both objectives should be considered simultaneously in the procedure of multilayer design. Though it is simple to convert these two optimized objectives into a single goal, which just optimizes the summation of two merit functions, but it often fails to reflect the complex relationship between objectives and one must give a good consideration of weight between two objectives. During recent years, a multi-objective evolutionary algorithm which is defined as non-dominated sorting genetic algorithm II (NSGA-II) has been developed, and much better performance of NSGA-II for multi-objective optimization problem is observed [27]. This algorithm can simultaneously optimize two objectives, and due to the advantage of evolutionary algorithm, it is immune to local topology in the solution space. Furthermore, during the optimization of NSGA-II, these two objectives do not influence each other, and this algorithm has the ability to find a good convergence near the true Pareto-optimal front which is a set of solutions of the multi-objective problem.

In this paper, a procedure for the robust design of broadband EUV multilayer is presented, and the reflectivity and robust performances of the aperiodic Mo/Si multilayer are set as two objectives of NSGA-II. This research should open the application of multi-objective evolutionary algorithm on the design of optical multilayer, and this set of mathematical procedures also has a great potential to give other multilayer designs which combine other optical performances. It is worthwhile to point out that the ultra-smooth substrate of EUV multilayer is high cost, thus this robust multilayer design of broadband Mo/Si multilayer could reduce the production risks of EUV mirrors.

2. Design of Mo/Si multilayer based on multi-objective evolutionary algorithm

At first, we present a brief description of electromagnetic wave propagation in a non-periodic multilayer system, and demonstrate the theoretical calculation of reflection. The wave propagation in a homogeneous layer j which is contained in the multilayer system can be characterized by transfer matrix $\mathbf{M}_j$, and this matrix which connects the electric field between the neighboring layers j and $j+1$ can be written by

$$\mathbf{M}_j = \mathbf{T}_j \cdot \mathbf{R}_{j,j+1} = \begin{bmatrix} e^{-ik_j d_j} & 0 \\ 0 & e^{ik_j d_j} \end{bmatrix} \cdot \begin{bmatrix} t_{j,j+1} & r_{j,j+1} \\ r_{j,j+1} & t_{j,j+1} \end{bmatrix}, \tag{1}$$

where $\mathbf{T}_j$ and $\mathbf{R}_{j,j+1}$ are the translation and refraction matrices, respectively. Here, d_j is the layer thickness, and the coefficients $r_{j,j+1}$ and $t_{j,j+1}$ should be given as

$$\begin{aligned} r_{j,j+1} &= \frac{k_{j+1} - k_j}{2k_{j+1}}; \\ t_{j,j+1} &= \frac{k_{j+1} + k_j}{2k_{j+1}}, \end{aligned} \tag{2}$$

where k_j represents the z-component of wave-vector for layer j. In the general case, the value of k_j depends on the polarization of the incident radiation, and it can be given as

$$k_j = \begin{cases} \dfrac{2\pi}{\lambda} n_j \cos\theta_j & \text{s polarization,} \\ \dfrac{2\pi}{\lambda} \dfrac{n_j}{\cos\theta_j} & \text{p polarization;} \end{cases} \tag{3}$$

where $n_j = 1 - \alpha_j - i\beta_j$ is the complex refractive index of the layer j, θ_j is the incident angle of the layer j, λ is the incident beam wavelength, and here the optical constants are taken from CXRO database [28].

Considering the loss in reflectance due to interfacial roughness, the coefficient $r_{j,j+1}$ in Eq. (1) should be modified by

$$\widetilde{r}_{j,j+1} = r_{j,j+1} \exp\left[-2n_j \cos\theta_j n_{j+1} \cos\theta_{j+1} \left(\frac{2\pi\sigma_{j,j+1}}{\lambda}\right)^2\right], \tag{4}$$

where $\sigma_{j,j+1}$ is the interfacial roughness between the layers j and $j+1$. When the electromagnetic wave propagates through a multilayer system with N layers, the propagation should be represented by the characteristic matrix [29]

$$\mathbf{M} = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \mathbf{R}_{\text{sub}} \mathbf{M}_1 \cdots \mathbf{M}_j \cdots \mathbf{M}_N, \tag{5}$$

where $\mathbf{R}_{\text{sub}}$ is the refraction matrix between the substrate and first layer. For the EUV radiation, the Fresnel reflection coefficient of the electric field at the surface of the multilayer system can be given by

$$r_N = \frac{M_{12}}{M_{22}}, \tag{6}$$

and then the reflectivity can be calculated by

$$R = |r_N|^2. \tag{7}$$

Secondly, we demonstrate the mathematical procedure of robust multilayer design, which is based on NSGA-II. Here two merit functions of multilayer design can be defined by

$$\begin{aligned} f_1 &= \int_{\varphi_{\min}}^{\varphi_{\max}} \left[R(\varphi) - R_0\right]^2 d\varphi; \\ f_2 &= f_1 + \frac{1}{2} \sum_{i=1}^{m} \frac{\partial^2 f_1}{\partial d_i^2} \delta_i^2, \end{aligned} \tag{8}$$

where R and R_0 are the theoretical and target reflectivities of the design multilayer respectively, and then the first merit function f_1 characterizes the root-mean-square deviation of the calculated reflectivity profile from the desired one. Here d_i and δ_i are the thickness and thickness error's standard deviation of the ith layer respectively, thus the second merit function f_2 is the robust design merit function of multilayer [25]. In Eq.(8), we consider m layers included in the multilayer system have thickness errors which originate from imprecision deposited control of quartz crystal monitoring or time monitoring. Therefore, these thickness errors are independent and can be simulated as random ones distributed in accordance with normal distribution law with zero mathematical expectation and standard deviations. Hence, the reflectivity performance of multilayer design is optimized by minimization of the first merit function f_1, and the multilayer design's sensitivity of reflectivity performance to layer thickness errors can be optimized by minimization of the second merit function f_2. In order to simultaneously optimize these two merit functions, both of them are set as the optimized objectives of NSGA-II, and each individual's gene is characterized by a set of parameters which are the layer thicknesses required optimizations. We use a population size of 100 and run the program until 3000 generations. Other parameters of the program are that the crossover probability P_c is 0.9, mutation probability P_m is 0.1, and distribution indexes for the crossover and mutation operators are $\eta_c = 2$ and $\eta_m = 2$, respectively. In the following, we demonstrate the conceptual steps of NSGA-II which can be applied to robust design of aperiodic Mo/Si multilayer, and much more details can be found in [27] and the references therein.

Step 1. Initialization of the internal multi-objective evolutionary algorithm settings. In this step, all the parameters above mentioned are assigned with values.

Step 2. Creation of a random parent population. Each solution in the population is represented by the multilayer's parameters of layer thicknesses which require the optimizations.

Step 3. Evaluation of the parent population, by calculating these two fitness functions in Eq.(8).

Step 4. Each parent solution is assigned a rank equal to its nondomination level, and the nondominated solutions are further sorted by using the crowding comparison procedure.

If both fitness values of solution p are less than that of solution q respectively, it is defined that solution q is dominated by solution p, which means solution p is superior to solution q; otherwise the relation between these two solutions is nondomination. In this step, each solution is compared with every other solution in the population