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Mechanism and model of atomic hydrogen cleaning for different types of carbon contamination on extreme ultraviolet multilayers

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ABSTRACT

The use of atomic hydrogen to clean carbon contaminants on multilayers in extreme ultraviolet lithography systems has been extensively investigated. Additional knowledge of the cleaning rate would not only provide a better understanding of the reaction mechanism but would also inform the industry's cleaning process. In this paper, which focuses on the atomic-hydrogen-based carbon contamination cleaning process, a possible mechanism for the associated reactions is studied and a cleaning model is established. The calculated results are in good agreement with the existing experimental data in the literature. The influences of the main factors – such as activation energy and types of contamination – on the cleaning rate are addressed by the model. The model shows that the cleaning rate depends on the type of carbon contamination. The rate for a polymer-like carbon layer is higher than the rate for graphitic and diamond-like carbon layers. At 340 K, the rate for a polymer-like carbon layer is 10 times higher than for graphitic carbon layers. This model could be used effectively to predict and evaluate the cleaning rates for various carbon contamination types.

1. Introduction

Extreme ultraviolet lithography (EUVL) is a developing lithography technology at the 11–22-nm node and its use is likely to increase in the future [1,2]. The prototype produced by ASML, EUVL NEX: 3300B, can produce 600 wafers per day as of 2015. The commercial model EUVL NEX: 3305B, which is expected to be available in 2016, will produce 1500 wafers per day. During EUV exposure, the remaining hydrocarbons in the surroundings deposit on the surface of optical elements and inevitably generate carbon contamination under EUV source illumination. These contaminants absorb EUV light, which leads to the loss of reflectance. For a commercial EUVL, the loss in reflectance should be less than 1.6% during the lifetime of the optical system, which is usually more than 30,000 h. This requirement means that the thickness of the carbon contaminant layer must remain less than 2 nm [3,4]. Therefore, removing carbon contaminants can prolong the service life of EUVL systems.

There are several ways to clean the carbon contamination, such as Radio Frequency (RF)–O_2/H_2, UV/O_2, EUV/O_2 and atomic hydrogen [5–8]. Atomic hydrogen is considered to have the most potential for removing carbon contaminants on EUV multilayers because it causes little oxidation or other damage to the surface of the multilayer. The cleaning rate is an important technical index for evaluating cleaning methods. Due to the effects of EUV irradiation flux, surrounding conditions, and other factors, the types of carbon contamination generated on the EUV optical elements vary, as do their cleaning rates. Graham and his colleague have obtained a 0.1 nm/min cleaning rate for sputtering deposition induced carbon and a 0.2 nm/min rate for EUV-induced carbon in their experiments [5].

To elucidate the cleaning process for different types of contamination and predict their associated cleaning rates, it is necessary to develop an accurate model. At present, there is no clear model based on chemical kinetics to explain the cleaning process. In this paper, a possible mechanism for the reactions is studied and a cleaning model is established. The influences of the main factors – such as activation energy and types of contamination – on the cleaning process and the cleaning rate are discussed. The calculated results are in good agreement with the existing experimental data in the literature. This model could be used effectively to predict and evaluate the cleaning rates for different carbon contamination types and inform the industry cleaning process.

2. Types of carbon contaminants on EUV multilayers

The types of carbon contaminants on EUV multilayers vary with changes in surface exposure intensity, temperature, background gases, exposure time and so on [9]. Main types of carbon contaminants are polymer-like, diamond-like and graphite-like. The types are usually determined by XPS [10], but this method is inconvenient. This paper

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studies the relationship between the types and the reflectivity losses for use as a method to determine contaminant type. We assumed that the sample is a standard EUV multilayer mirror consisting of 50 thin bilayers of Mo and Si deposited on a Si (100) wafer with a 2-nm-thick cap layer of Ru subsequently deposited on top. We calculated the reflectivity of multilayers for different types of carbon contamination; as shown in Fig. 1, the reflectivity of the multilayers depends on the contaminant type.

The reflectivity of a standard Mo/Si multilayer is 75.53% at a wavelength of 13.5 nm and decreases with the deposition of different types of carbon contamination. Diamond-like carbon contamination causes the greatest decrease in reflectivity, and polymer-like carbon causes the smallest decrease. When the thickness of carbon contaminant is 2 nm, the diamond-like carbon reduces reflectivity by 3.87% and the graphitic-like carbon reduces reflectivity by 2.63%. The polymer-like carbon's reflectivity depends on its density ρ: its reflectivity decreases by 1.4% for $\rho = 1.25\ \mathrm{g/cm^3}$ and 0.94% for $\rho = 0.9\ \mathrm{g/cm^3}$. When the thickness of carbon contaminant is 5 nm, the differences in reflectivity are more pronounced than for 2 nm thickness, but the trend of reflectivity decreases is still the same. The reflectivity losses are 11.21%, 6.93%, 3.87% and 2.75% for diamond-like, graphitic-like and polymer-like carbon with different densities, respectively.

In summary, these curves display the relationship between the different carbon contamination types and their associated reflectivity losses. Therefore, the carbon type can be estimated according to the thickness and reflectivity loss of the carbon layer.

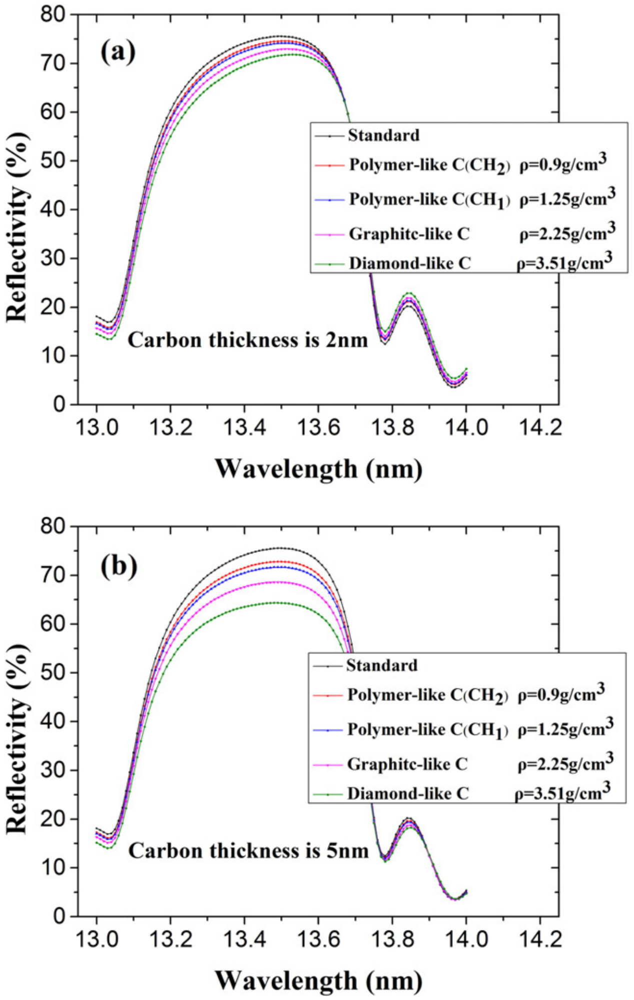

Fig. 1. The dependence of reflectivity value of multilayers on the types of carbon contamination (a) 2 nm thickness of carbon (b) 5 nm thickness of carbon.

3. The mechanism of atomic hydrogen cleaning

Physical sputtering and chemical reactions work simultaneously in cleaning process, and they have been offered as explanations for the mechanisms of various cleaning methods. However, the basic chemical kinetics mechanism for atomic hydrogen cleaning technology is not clear for each of the different types of carbon contamination [11]. Therefore, further research of the cleaning mechanism is necessary to build the cleaning model.

3.1. Physical sputtering

The mechanism of physical sputtering is the process in which the incident hydrogen atoms impact with high energy on the surface of the EUV multilayer and transfer their energy to carbon atoms. When the carbon atoms absorb sufficient energy to overcome the surface binding energy E_s, they will escape from the surface. The physical sputtering yield is calculated by simulation software [12]. Fig. 2 shows the relationship between physical sputtering yield and the energy of incident hydrogen atoms for different types of carbon contamination.

The energy threshold E_{th} for different types can be obtained from Fig. 2. This figure shows that E_{th} depends on the type of carbon contamination. The E_{th} of polymer-like carbon is lower than that of other carbon types. The higher the hydrogen concentration in polymer-like carbon contaminants is, the smaller E_{th} is. Because CH_3– is not stable, CH_2– has the highest hydrogen concentration of polymer-like carbon contaminants. It means that the E_{th} for CH_2– is the smallest. The energy of incident atomic hydrogen generated by heating a W-filament is lower than the smallest E_{th} in most cases. Therefore, the physical sputtering contributes minimally to the cleaning process.

3.2. Chemical reaction

Because physical sputtering has been shown to be a minor factor, a chemical reaction is thus the main mechanism of atomic hydrogen cleaning technology to remove carbon contaminants. A mathematical model considering the chemical reaction is built to accurately describe the reaction between atomic hydrogen and carbon. It consists of two parts: the transport of atomic hydrogen and the chemical reaction itself.

Atomic hydrogen is produced by a high temperature W-filament. It is not stable and will recombine to hydrogen during the transport process [13]. To simulate the flux of atomic hydrogen that arrives at the surface of multilayer, the Arrhenius function is used here. k_{h}^{-} stands

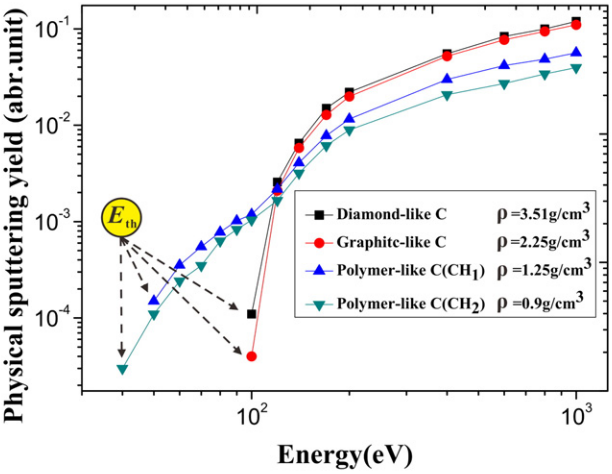

Fig. 2. The dependence of physical sputtering yield for different types of carbon contamination on the energy of incident hydrogen atoms.