Electron-beam lithography simulation for EUV mask applications

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Abstract. Extreme-ultraviolet- (EUV) mask fabrication using electron-beam lithography has to eliminate the proximity effect defects, for the accurate representation of the patterned features. One special characteristic of EUV masks is that they contain a multilayer stack of repeated Si/Mo thin layers. This has to be considered explicitly in the simulation of electron-beam energy dissipation calculation using Monte Carlo methods. In a first approximation to the problem of electron scattering in a multi-layer substrate, the continuous slowing down approximation utilizing the Rutherford differential cross section is used in order to describe the electron inelastic energy loss mechanism and determine the amount of deposited backscattered energy, in the resist film on top of the multi-layer substrate. Three-dimensional modeling is used and in this first attempt to describe the process, no secondary electron generation or other excitation processes are considered. The effect of the number of layers and their relative thickness in terms of incident electron energy is investigated.

1. Introduction

Extreme ultraviolet lithography (EUVL) masks typically consist of an absorber, a repair buffer, an etch stop layer, a molybdenum/silicon (Mo/Si) multilayer, and an ultralow thermal expansion substrate. A simplified picture of the way EUVL works is shown in figure 1. Patterning an EUVL mask absorber stack is usually accomplished using electron-beam lithography (e-beam). With EUVL targeted for the sub 50 nm node and the critical dimension (CD) of features on the mask approaching 100 nm, it becomes challenging to meet the requirements for both CD uniformity and image placement. In e-beam lithography, the incident electrons are scattered by the resist and the substrate. Electron energy is deposited at some distance from the exposure area, thereby causing CD variation of neighboring features. With current optical binary mask technology, a high voltage (>50 kV) exposure is preferred because of the reduced forward scattering of electrons in the resist, resulting in improved feature fidelity. Another advantage of using high voltage exposure for micron size features is the elimination of proximity effect correction due to the spreading of backscattered electrons over a large area. However, since the features needed on the mask have critical dimensions well below 1 \( \mu \)m, the scattering of electrons in the resist and from the substrate again becomes a major consideration [1].

Simulation of electron tracks [2,3] and deposited energy in the resist – substrate system can assist in the design and proximity correction of EUVL masks. The purpose of the current article is to present a first attempt to model the electron energy deposition process of primary and backscattered electrons in the resist – multi-layer substrate during the fabrication process of the features of the EUVL mask. Monte Carlo simulation of electron trajectories is used utilizing the continuous slowing down...
approximation (CSDA). Three dimensional (3D) calculation of the deposited energy is performed and first results of the effects of the number and layer thickness of the multilayer substrate on the electron backscattering coefficient are presented.

2. Model Description

Bethe has derived the following expression, which gives the kinetic energy lost by a nonrelativistic electron as it travels a path of length $ds$ in matter [2]

$$\frac{dT}{ds} = -7.83 \left( \frac{\rho Z}{AT} \right) \ln \left( \frac{174T}{Z} \right) \left( \frac{keV}{\mu m} \right)$$

where $T(keV)$ is the electronic kinetic energy, $\rho$ (g/cm$^3$) the density of the target material, $A(g)$ the atomic weight of the target and $Z$ the atomic number of the target. The penetrating electrons are subject to a screened Coulomb potential

$$V(r) = \frac{Zq^2}{r} e^{-\frac{r}{a_0}}$$

where $q$ is the electron charge, $r$ the distance between the colliding electron and the nucleus, and $a_0$ the Bohr radius of hydrogen. The $\alpha$ parameter in the exponential factor approximately represents the screening of the nucleus by the orbital electrons. This leads to the following shielded Rutherford cross-section

$$\frac{d\sigma}{d\Omega} = \frac{Z(Z+1)e^4}{p^2\beta^2} \frac{1}{(1-\cos\theta+2\beta)^2}, \quad \beta = 0.25 \left( \frac{1.12Z^{1/3}A}{0.885\rho a_0} \right)^2$$

where $p = m \upsilon$ is the electron momentum, and angle $\theta$ represents the scattering angle. The total screened cross-section, $\sigma_T$ is found be integrating the above expression over all solid angles. If the electron beam is exponentially attenuated, then the mean free path $\lambda$ is given by

$$\lambda = \frac{\int e^{-N_A\sigma_T} ds}{\int e^{-N_A\sigma_T} ds} = \frac{1.02\beta(1+\beta)AT^2}{Z(Z+1)\rho}$$

where $N_A$ is Avogadro’s number.

**Figure 1.** Simplified picture of the lithographic process in EUVL. The main characteristic of the mask is that it is reflective rather than transmissive, because in the specific radiation wavelength all components of the mask absorb.

**Figure 2.** Coordinate system used in the electron track simulation. Between successive scattering events, energy loss is calculated from the continuous slowing down approximation.
An electron is followed in its trajectory into the solid target until its energy becomes lower than the mean ionization energy $J$ calculated in eV by

$$J = \left(9.76 + \frac{58.89}{Z^{1/3}}\right)Z$$

(5)

The expressions given so far are the basic necessary for the Monte Carlo calculation. They must be combined with the geometry of the simulation domain, which should relate the scattering frame of reference with the laboratory frame. The coordinate system used in the electron track scattering simulation is shown in figure 2. The specific details of the simulation geometry and the algorithm structure can be found in reference [2]. Three-dimensional modeling is used and in this first attempt to describe the process, no secondary electron generation or other excitation processes are considered.

3. Simulation Results

First the backscattering coefficient was determined assuming that the electron beam impinges and penetrates bulk material. Figure 3 shows the determined backscattering coefficient, $BC$, as a function of the target atomic number $Z$. Experimental and Monte Carlo data from other simulation codes were obtained from reference [4]. Our simulations were performed with $N=10^5$ electron tracks. However, as is shown in figure 3, using $N=10^4$ electrons also result in approximately the same results. Small deviations were observed as atomic number increased. Since the multiplayer substrate in EUVL masks consists of repeated layers of Si and Mo, for which the results for $BC$ using the current algorithm, are quite well, no further improvement in the algorithmic details was pursued. The next step was to simulate the case of a thin film of one material on top of another considered as a substrate. Figure 4 shows the experimentally determined $BC$ for increasing Ag film thickness on top of Si bulk [4]. The validity of our model is tested again and good agreement was found as shown in the figure using $N=10^5$ and even $N=10^3$ electron tracks. The case of increasing thickness of Mo film on top of Si bulk was simulated next, and is shown as the triangle points in figure 4.

Figure 3. Electron backscattering coefficient vs. atomic number of bulk target material. Points connected by line are both experimental and Monte Carlo data found in [4], for $T_0=10\,keV$. Simulations with $N=10^5$ and $10^4$ electrons show the agreement with the published data.

Figure 4. Electron backscattering coefficient vs. increasing Ag and Mo film thickness on top of Si bulk material. Points connected by line are experimental data found in [4], for $T_0=20\,keV$. Simulations with $N=10^5$ and even $10^3$ electron tracks, show the agreement with the published data (squares and circles).

Having validated the bulk and single layer version of the code with published experimental data on electron backscattering coefficient the final objective is to present simulation results from multi-layer structures of repeated Si/Mo layers on top of a Si substrate. Specifically, two series of simulations where performed. In both the total multi-layer stack thickness is 300nm. In the first one each layer has 10nm thickness and the stack consists of 30 repeated Si/Mo layers. And in the second case, each layer is 20nm thick and the stack consists of 15 repeater Si/Mo layers. The electron backscattering
coefficient dependence on the initial electron beam energy $T_0$ is presented in figure 5. Approximately one order of magnitude reduction in the value of $BC$ is observed, compared with the case of a $300\text{nm}$ Mo-film on top of a Si substrate or even a bulk Si target. This is a welcome result because backscattering is a defect generation mechanism in mask fabrication using e-beam due to the proximity effect. It is also clear that the number of repeated layers in the stacks has an effect on $BC$. Specifically, it is better to have a stack consisting of many thin layers, since this decreases $BC$, especially in lower $T_0$, where $BC$ is higher. Finally in figure 6, the total deposited energy per layer versus the stack-depth is presented. The periodicity of the ups-and-downs of the deposited energy is approximately equal in each case to the Si/Mo layer-thickness. More energy is deposited in Mo layers since they have greater $Z$. In the case with the less layers, the deposited energy shows a greater spread in the stack. The decrease of $BC$ with energy can also be understood by observing in figure 6 that with increasing electron energy the electrons penetrate deeper in the multi-layer structure. Therefore they suffer greater losses when traversing more layers or greater material thickness in order to be emitted as backscattered electrons.

![Figure 5](image5.png)  
**Figure 5.** Backscattering coefficient vs. electron beam energy as obtained from the simulation of $N=10^5$ electrons penetrating a $300\text{nm}$ multi-layer Si/Mo stack on top of a Si-substrate.

![Figure 6](image6.png)  
**Figure 6.** Deposited energy per layer vs. depth in multi-layer. Increasing $T_0$ results in deeper beam penetration and greater spread of energy loss in multi-layer. This justifies the reduction of backscattering coefficient with electron beam energy.

### 4. Conclusions

The basic principles of a Monte Carlo simulation scheme for the determination of electron backscattering coefficient due to an electron-beam penetrating a multi-layer stack of repeated Si/Mo thin layers was presented. The simulation results were compared with published data on the backscattering coefficient from bulk targets or thin films over a substrate, and good agreement was found. Application of the algorithm to the determination of backscattering coefficient from the multi-layer stack revealed that it greatly decreases in comparison with the bulk case. In fact its decrease was found proportional to the number of layers in the stack.

### 5. Acknowledgements

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### 6. References

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