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Calculation of energy deposition in thin resist films over multilayer substrates

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Multilayer substrates are of great importance for direct write applications. Recently, they are getting more and more importance in mask making as well, for example in the phase shift technology. In the case of direct writing, the substrate consists of various layers of different materials while for mask fabrication, the mask plate consists of at least two different layers, e.g. Cr on glass. A new method for the calculation of energy deposition due to e-beam exposure in thin resist films over composite substrates is presented. The method is based on the solution of the Boltzmann transport equation and has proven to be very fast compared to Monte Carlo method, and its accuracy has been shown by successful comparison with experimental obtained results. The method is incorporated in a complete e-beam lithography simulator.

1. INTRODUCTION

The interest for electron beam lithography based techniques for direct writing and mask fabrication increases continuously. In the case of direct writing, the substrate consists of various layers of different materials (depends on the previous processing steps) while for mask fabrication, consists of at least two different layers, e.g. Cr on glass. Therefore it is of vital importance to calculate the influence of this kind of substrate (multilayer) on the lithographic performance of the resist used.

The substrate influences the final resist profile through the energy deposition from backscattered electrons. If the total Energy Deposition Function (EDF(r)) is known, it is possible to calculate process windows and resist profiles and apply effective proximity effect correction.

Traditionally, for single layer (homogeneous) substrates the Monte Carlo method is used for (EDF(r)) calculation. This approach is very time consuming, which makes it not applicable in real process simulation. Recently, this drawback has been overcome by using an analytical approach based on the Boltzmann transport equation.

In this work an extrapolation of this method for multilayer substrates is presented. Energy deposition results will be presented for substrates consist of 1, 2 and 3 different layers. Additionally resist profiles after development for characteristic cases will be presented.

2. ANALYTICAL CALCULATION OF ENERGY DEPOSITION

The Monte Carlo method has been used for electron beam lithography simulation [1] of homogeneous substrates (e.g. Si, GaAs), due to its simplicity and accuracy. Nevertheless it has a significant drawback: the needed CPU time. Since a very large number of electrons (50000 - 100000) must be used in order to minimize the statistical fluctuations, a lot of computational power is needed. Additionally, the CPU time increases dramatically as the number of layers in multilayer substrates increases.

An alternative method, based on the solution of the Boltzmann transport equation [2], has been proposed in order to overcome the CPU disadvantage. All sources of energy deposition are calculated separately (i.e. electrons are separated in forward electrons, backscattered electrons due to large angle scattering events (I_{bs}), backscattered electrons due to a suite of small angle scattering events (I_{bd}), secondary electrons). For every case a distribution is calculated [2]. In this method there aren't any statistical calculations and only numerical representations are calculated. Therefore the method is faster than Monte Carlo. The CPU time needed for point exposure simulation is very small compared to the time consumed for the convolution of EDF(r) for a given layout. This analytical method will be incorporated in the recently developed 3D e-beam

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lithography simulator SELID [3]. In table 1, CPU times on a SUN Sparc I, for complete EDF(r) calculation for various substrates (single and multilayer) are presented. In the parentheses of second and third column of table 1, there are the CPU times for EDF(r) calculation only at the resist/substrate interface.

Table 1: CPU time in sec. for EDF(r) calculation. Cell dimensions were 0.01X0.01 μm (40X500 matrix for 20 KeV, 40X1000 for 50 KeV).

Substrate	E_o=20KeV	E_o=50KeV
Si	10(3)	38(9)
GaAs	9(2)	45(10)
Au	7(2)	29(7)
0.2 μm Au/Si	8(3)	47(13)
0.6 μm Au/Si	8(2)	35(11)
0.3 μm Ag/Si	10(3)	46(13)
0.8 μm Ag/Si	9(3)	44(12)
0.2 μm Au/0.1 μm Cr/Si	8(3)	56(15)
0.6 μm Au/0.1 μm Cr/Si	7(3)	41(12)

3. RESULTS - DISCUSSION

In fig. 1 EDF(r) for 0.4 μm PMMA/Au/Si (e.g. substrate for x-ray masks) for various thickness' of Au (T_{Au}) are presented for E_0 = 40 KeV. It is obvious that the backscattering contribution to EDF(r) is not a simple Gaussian form but it also contains a $1/r^3$ part due to backscattering electrons from large angle scattering events [2]. This result has already been proved by other experimental and simulation results [4]. The cross-section for this kind of electrons depends strongly on substrate scattering characteristics. For that reason the shape of EDF(r) changes as T_{Au} increases.

From fig. 1 it is obvious that as T_{Au} increases, the EDF(r) approaches EDF(r) for bulk Au. Actually there is a critical thickness (T_{crit}) of the intermediate layer which causes the same EDF(r) as a single layer substrate. For the examined case, T_{crit} ~ 0.85 μm, which means that for $T_{Au} \geq 0.85$ μm the presence of the Si substrate has no effect on EDF(r).

Almost all backscattered electrons that enter again into the resist film, have not penetrated the substrate at depths deeper than T_{crit}. Therefore the backscattering coefficient (b_c) also saturates at T_{crit}.

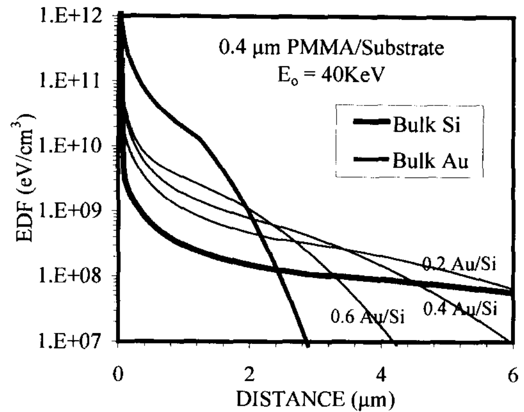

Figure 1: EDF(r) for various Au thickness (0.2, 0.4, 0.6 μm) over bulk Si at resist/substrate interface.

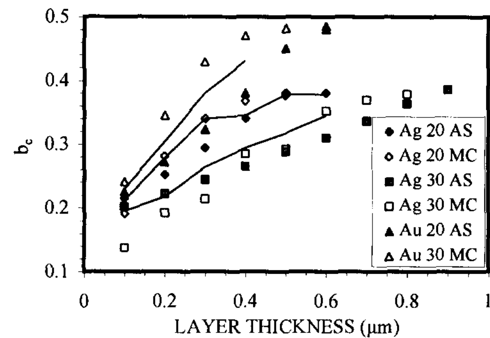

Figure 2. b_c for Au and Ag layers of variable thickness on bulk Al. Points are simulation results (AA: analytical approach, MC: Monte Carlo) and lines are experimental. Examined E_0 = 20 - 40 KeV.

This result has been observed experimentally [5] and from Monte Carlo simulations [6].

In fig. 2, b_c values for Au and Ag layers on bulk Al are presented. The data are from experimental results and from simulation (Monte Carlo [6] and from Analytical approach). For all energies and thickness' the difference is less than 15%.

In fig. 3, T_{crit} for various materials is presented. By applying fitting to these curves, a uniform fitting function for all materials is obtained:

$$T_{crit} = 2.1N^{-0.84}\ln(E) - 5.5N^{-0.79} \quad (1a)$$

where E is the beam energy and N the material's scattering parameter:

$$N = \rho Z / A \quad (1b)$$

where ρ is density, Z mean atomic number and A the mean atomic weight. T_{crit} presented at fig. 3 and fitting function (eq. 1), are valid only for the specific resist thickness (0.4 μm). Nevertheless, T_{crit} doesn't changes significantly for similar resist thickness'.

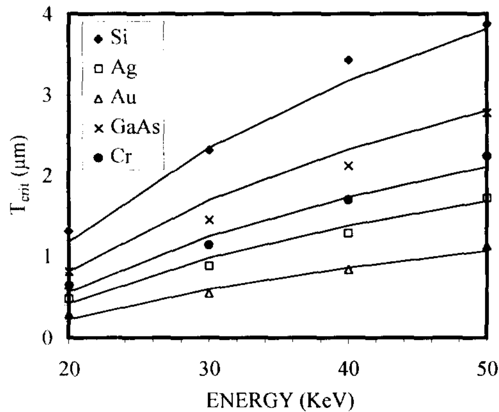

Figure 3. T_{crit} values for various materials. Points are from simulation and lines from fitting function (1a).

Unfortunately there are few multilayer experimental results for comparison. (e.g. T_{crit} for Si exposed with E_o = 20 KeV was estimated [7] slightly larger than 1.1 μm while T_{crit} from our calculations is ~ 1.3 μm.) In another work [8], β_{bd} (standard deviation of I_{bd}) for 0.8 μm Ti/Si substrate was calculated 1.4 μm, while from the analytical approach, β_{bd} = 1.2 μm

For the confirmation of the simulation results, contrast curve experiments were carried out for Au intermediate layer. Specifically, the required dose for total resist removal (clearing dose) was measured for various T_{Au}. These data and the according simulation results are presented in fig. 4.

In fig. 5 EDF(r) results are presented for hypothetical substrate consisted of 0.4 μm Mo/ variable thickness of Au/bulk Si. The existence of a critical thickness of Au is obvious again. This critical

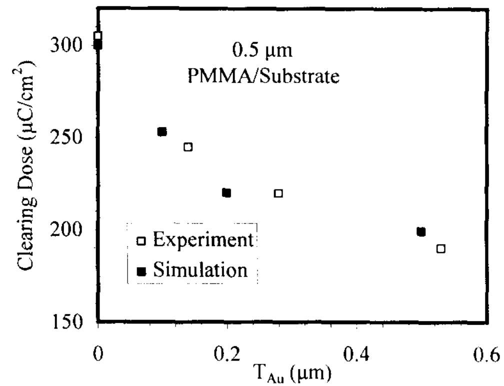

Figure 4. Clearing dose vs. Au thickness over Si substrate. The open symbols are from simulation and the filled from experiments. E_0 = 40 KeV.

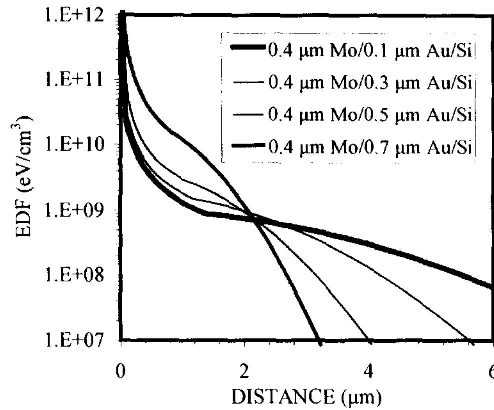

Figure 5: EDF(r) results for 0.4 μm PMMA/ hypothetical substrate consisted of 0.4 μm Mo / variable thickness Au / Si. E_o = 40 KeV.

thickness (0.65 μm) is not equal to the previous one (0.85 μm) due to the existence of Mo layer.

In fig. 6, a complete simulation for a multilayer substrate is presented. In fig. 6a, the EDF(r) is presented for 0.4 μm PMMA/x μm Au/ bulk Si where x = 0.0, 0.2, 0.3. For this resist film and energy, T_{crit} ~ 0.28 μm. The examined layout consists of an array (10 lines) of 0.15 μm lines spaced by 0.15 μm. The exposure dose and development conditions were the same for all three examined cases.

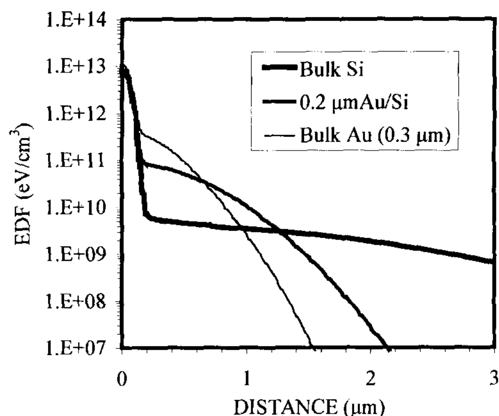

Figure 6a: EDF(r) for 0.4 µm PMMA / x µm Au /Si, where x = 0.0, 0.2, 0.3. E_0 = 20 KeV.

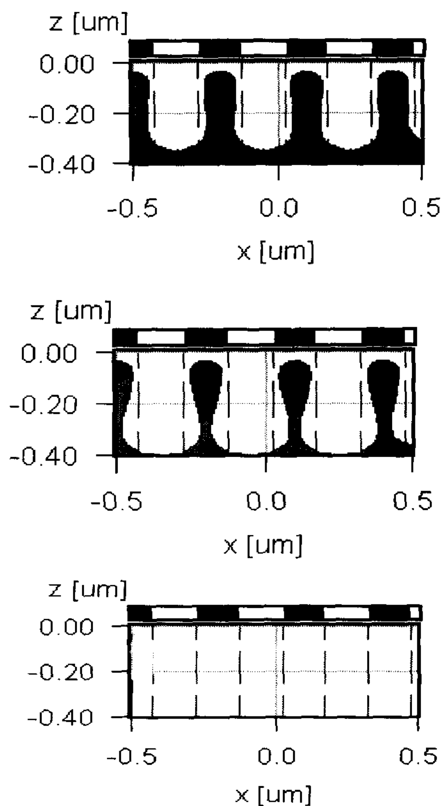

Figure 6: The effect of interemediate layer in resist profile for b) x=0.0 c) x=0.2 d) x>=0.3.

From fig. 6a the excessive energy deposition when a Au layer exists, is clear. This energy deposition arises from backscattered electrons due to large angle scattering events. These electrons emerge very close to the incident point of primary electrons. The effect of the intermediate layer on resist profiles is represented on figs. 6(b-d). Specifically, while the exposure dose is not enough for resolution of lines for the Si substrate, in the case of a thin Au intermediate layer this dose is enough. Nevertheless the resist profile is not acceptable. For the bulk Au substrate the energy deposition is too high and resist has been totally removed.

4. CONCLUSIONS

A new tool for studying the effects of multilayer substrates based on an analytical approach (for direct write and mask making applications) was presented. A specific case of two layers substrate has been presented. From this tool, proximity effect correction parameters can be extracted very fast and applied to appropriate correction software. The method proposed will be integrated in SELID with the option of an arbitrary number layers of any kind accessible to the user.

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