Monte Carlo study of inelastic scattering models of low energy electrons

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Multiple electron beam maskless lithography has tremendous potential among the next generation lithographies (NGL), especially for 22-nm node and beyond [1]. Although the electron beam has extremely high resolution, the scattering in resist and substrate is an issue. Therefore, an accurate simulation approach for predicting the behavior of electron-solid interactions is essential in electron beam lithography. In this study, inelastic scattering models with considering the discrete and continuous energy loss were compared at low electron energies with respect to backscattered coefficients (BS coefficient, η), energy dissipation and mean penetration depth. The simulation approaches are categorized into four types as shown in Table 1. The first one is the fast secondary electron model[2]. The other three are hybrid models[3] with three kinds of modified continuous slowing-down approximations (CSDA), $[dE/ds]_{cont}$. The modified CSDA is obtained by subtracting the knock-on collisions, $[dE/ds]_{dis}$. Moller or Gryzinski cross section were used in inelastic scattering processes. All of these approaches used Mott cross section for the elastic collision because of its better approximation at lower energies. The target is aluminium in all the following simulations.

Fig. 1 shows the calculated and experimental BS coefficients. The experimental data is obtained from D. C. Joy's database[4]. The fast secondary electron model with considering only valence excitation (MC1) performs poorer prediction for BS coefficient at lower electron energies. The choice of knock-on process influences the BS coefficients. The modified CSDA in MC2 was obtained by subtracting the energy loss rates of all inelastic knock-on collisions including valence excitation and core ionization. In MC3, the CSDA is only subtracted by the energy loss rate of that inelastic collision. The BS coefficient of MC2 is higher than that of MC3. MC4 shows the lowest BS coefficients. The electron energy dissipation range with the normalized electron energy is demonstrated in Fig. 2. The depth in x-axis is normalized by Grun's range R_G [5] and the deposited energy in y-axis is scaled to $d(E/E_0)/d(z/R_G)$. Near the target surface, MC3 and MC4 show higher energy deposition than Everhart's expression[5] because of their overestimation of energy loss. For MC3, the underestimation of CSDA leads to overestimate the energy deposition in the depth between surface and half of R_G. In MC4, the ionizing collision contributed from each electron shell of atom[3] is considered. The energy deposition near the target surface is more serious in MC4. Because the probability of inelastic scattering in MC4 is high, primary electrons transfer more energy to secondary electrons. The electron loses too much energy before half of R_G and dose not have enough energy to drive more ionizing collisions. Fig. 3 shows the electron trajectories at 1 keV in Al. The trajectories obtained by four approaches are almost the same at initial steps. The electron starts to scatter differently after first secondary electron emitted.

Reference

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Table 1. The models in thefour simulation approaches

Approach	MC1	MC2	MC3	MC4
Electron collision				
Valence excitation	Evans	Moller	Moller	Gryzinski
Core ionizations		Gryzinski	Gryzinksi	Gryzinski
Modified CSDA				
Elastic collision	(a)	(a)	(a)	(a)
Inelastic collision				
Valence excitation	(a)	(b)	(c)	(e)
Core ionizations		(b)	(d)	(e)

(a) Beth equation: Modified Beth equation by D.C Joy

(b) $\frac{dE}{dS}=\left(\frac{dE}{dS}\right)_{Beth}-\left(\frac{dE}{dS}\right)_{valence}-\left(\frac{dE}{dS}\right)_{core}$ (d) $\frac{dE}{dS}=\left(\frac{dE}{dS}\right)_{Beth}-\left(\frac{dE}{dS}\right)_{core}$

(c) $\frac{dE}{dS}=\left(\frac{dE}{dS}\right)_{Beth}-\left(\frac{dE}{dS}\right)_{valence}$ (e) $\frac{dE}{dS}=\left(\frac{dE}{dS}\right)_{Beth}-\sum_{n}\left(\frac{dE}{dS}\right)_{each\ shell}$

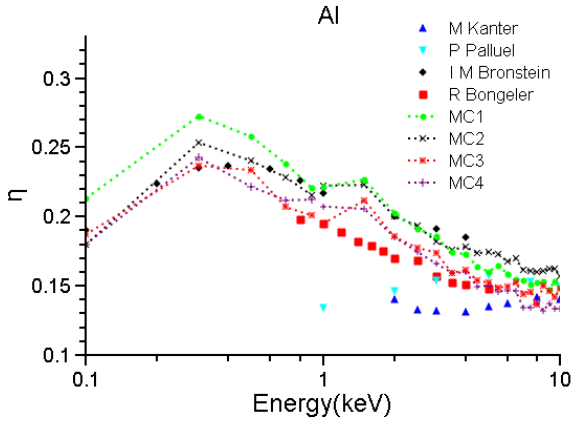

Fig. 1 MC simulation of the BS coefficient as a function of primary beam energy. The experimental data is from D. C. Joy's database[4].

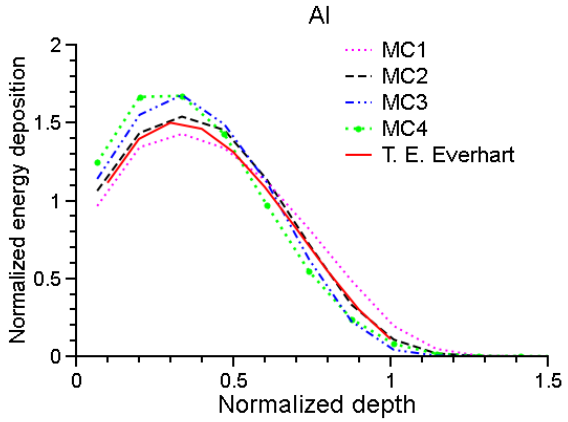

Fig. 2 Normalized energy deposition of Al at 5 keV.

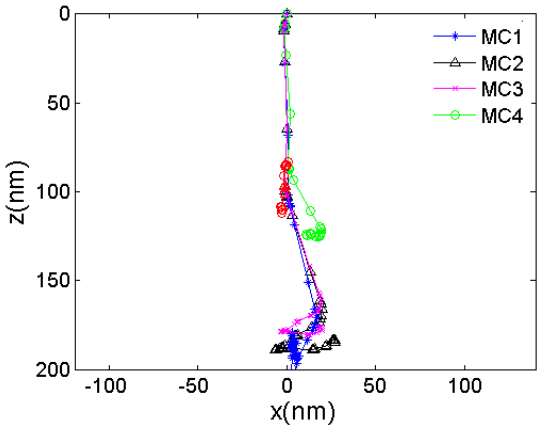

Fig. 3 Single electron trajectory in Al at 1 keV. The random number sequences are the same for each approach.