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ABSTRACT

The backscattering of electrons from complex targets (for example, metal layer on a semi-infinite substrate with a polymer resist film above) has been studied both theoretically and experimentally. The experimental structures were exposed with an electron beam in a "spot mode". The experimental observations of developed disc radius vs. exposure time and metal layer thickness support the simple theory of scattering in such structures. The theory assumes that the backscattering causes enlarging of the exposed area by a constant value. This value is derived from the proposed scattering model based on the Archard's and Kanaya and Okayama's diffusion theories. The radial exposure intensity distribution introduced by the electron beam has been approximated by a Gaussian function.

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INTRODUCTION

Backscattering of electrons from a solid target has been previously studied theoretically and experimentally in order to understand fundamentals of electron probe microanalysis and scanning electron microscopy. It is also very important to know to what extent backscattering affects the resolution in electron beam lithography.

The spatial resolution depends on the material structure which is exposed by the electron beam (Adesida and Everhart (1980), Aizaki (1979), Kato et al. (1978)). In our previous work, Kisza et al. (1981), a substrate-polymer film target was analyzed and a simple model of electron scattering in this structure was proposed. The current work presents scattering analysis for a more complex structure, i.e., a substrate-metal layer-polymer film target.

ANALYSIS OF SCATTERING IN COMPLEX STRUCTURES

Two simple models are helpful for interpreting backscattering phenomena. One of them derives from the assumption, by Everhart (1960), concerning a large-angle single scattering event. The Archard (1961) model is based on a small-angle multiple scattering process, i.e., the concept of the complete diffusion within a sphere. Such a model is valid for materials with large atomic number ($Z > 40$).

The latter model has been improved by Kanaya and Okayama (1972) who assumed the diffusion sphere center to be at the depth of the maximum energy dissipation x_e, and the sphere radius being appropriately $R - x_e$. Their model assumes that the backscattered electrons reach the target surface if they are scattered within the angle which is characteristic of a given material. This improved "diffusion model" is useful for materials of both low and high atomic numbers.

According to Kanaya and Okayama (1972), the following relations determine the parameters of the diffusion sphere R, x_D, x_e, r_B, Θ_0 (Fig. 1) in the energy range 10 to 1000 keV.

$$R = 2.76 \times 10^{-11} \frac{A \times E^{5/3}}{\varrho \times Z^{8/9}} \tag{1}$$

$$\tan\Theta_0 = \frac{2.2 \times \gamma \times (1 + \gamma)}{1 + 2\gamma - 0.21 \times \gamma^2} \tag{2}$$

$$x_e = \frac{R(1 + 2\gamma - 0.21 \times \gamma^2)}{2 \times (1 + \gamma)^2} \quad (3)$$

$$r_B = 1.1 \frac{R \times \gamma}{1 + \gamma} \quad (4)$$

$$x_D = \frac{R}{1 + \gamma} \quad (5)$$

$$\gamma = 0.187 \times Z^{2/3} \quad (6)$$

where: E = primary electron energy (eV)
ϱ = material density ($g \cdot cm^{-3}$)
Z = atomic number
A = atomic weight
γ = absorption coefficient

To analyze electron backscattering in the complex target (composed of a substrate-polymer film or substrate-metal layer-polymer film) we have decided to base our analysis upon the subsequent presumptions:

1. The electron beam is treated as a point source, i.e., the beam width is neglected. This presumption has been already made in numerous theories.

2. The electron energy loss while passing through the polymer film is negligible in comparison with the electron energy. This presumption was also made by Nosker (1969).

3. The backscattered electrons enter the polymer film within the angle Θ_0 characteristic of the material layer, and do not change their trajectories in the polymer film.

The proposed model scheme is presented in Fig. 2. A primary electron with energy E_0 enters the structure and passes (almost without any energy loss) through the polymer film and with some energy loss through the metal layer. The quantitative value can be achieved from equation (1). After having passed through the metal, the primary electrons scatter in the substrate within the sphere. The sphere radius depends on the energy of the electron beam entering the substrate. Only a fraction of these electrons would be able to pass the metal layer a second time and to reach the polymer and expose it. This fraction can be considered as the one derived from another, smaller sphere. The new sphere radius corresponds to the electron energy diminished by the electron energy losses on the double path through the metal. This energy E_1 used for the construction of the new sphere in the substrate is:

$$E_1 = E_0 - \Delta E(x+1) \quad (7)$$

where: E_0 = primary electron energy
$\Delta E(x+1)$ = electron energy loss through the metal layer.

According to the proposed model, the total area of the polymer exposed by a point source is a sum of the following elements in (Fig. 2):

1. a disc with the radius r_B' produced by the electrons which are backscattered from the metal layer. The quantity depends on the metal layer thickness x and the scattering angle Θ_0'.

$$r_B' = x \cdot \tan \Theta_o' \quad (8)$$

2. a ring of the inside and outside radii r_B', $r_B' + r_B''$, respectively, which results from electrons backscattered from the substrate. Its value depends on the size of the scattering sphere in the substrate. This parameter can be derived from equation (2).

3. a ring characterized by the radii $r_B' + r_B''$ and $r_B' + r_B'' + d_p$ produced by the electrons which are able to pass through the polymer film. The parameter d_p depends on the polymer film thickness h and the angle Θ_0' of the metal layer.

$$d_p = h \cdot \tan \Theta_0' \quad (9)$$

The total radius r_0 of the exposed area is

$$r_0 = r_B' + r_B'' + d_p \quad (10)$$

The values of r_0, r_B', r_B'' and d_p derived from equations (2), (8), (9) and (10) for different Au layer thicknesses and a 0.21 μm polymer film are given in Table 1 for both of the diffusion models mentioned previously. For the first one, the sphere center is assumed to be at the maximum energy dissipation depth x_e (Kanaya and Okayama theory). For the second one the sphere center is located at the diffusion depth (Archard theory). The latter is valid for target materials with $Z > 40$. The values of the radius r_0 given in Table 1 are in good agreement with those obtained from Monte-Carlo calculations (Murata 1974, Kyser and Viswanathan, 1975).

When the metal layer thickness in the discussed structure is 0 or ∞, the structure changes to a simpler one, i.e., substrate-polymer film. The model for this structure has been proposed previously by the authors (Kisza et al., 1981). It has been checked experimentally for different substrate materials and different polymer film thickness, and good agreement between experiment and theory has been found.

EXPERIMENTS

To verify the proposed model, an exposure with a point source electron beam in the "spot mode" has been performed. The exposed structure consisted of a polymethyl methacrylate (PMMA) film and a thin gold layer on an Si substrate. After electron exposure and chemical developing, the exposed disc radii were measured with an optical microscope. The structures differed as to the polymer and metal layer thicknesses.

The experiments have also been performed for different electron beam currents to check the beam diameter influence. The experiments have been conducted in an electron beam exposure system (EBES). To ensure fixed conditions of exposure, a series of samples were assembled in the EBES housing. Therefore, the experiments were made in the course of the same process of pumping, alignment and exposure. The beam current was measured with a Faraday cup. The primary electron energy was 20 keV. The beam width was estimated (by observation of the scanning image resolution) as below 1 μm for 1 nA beam current. The resist films were developed in isopropyl alcohol and methyl ethyl ketone (4:3 by volume).

RESULTS AND DISCUSSION

Two discs which differed in their duration of electron exposure but were developed in the same way are shown in Fig. 3 as an example. The cross-linking of the exposed center of the disc is visible for the longer exposure durations. It is evidence of overexposure at this point. The relatively large dose in the center is caused by the fact that not only the primary electrons but also the backscattered electron distribution have their maximum in the disc center. The disc radius as a function of the exposure time is shown in Fig. 4. Some typical structures and two different current values were chosen.

The exposed disc radius r_0 is an exponential function of the exposure time t for the Gaussian character of the electron density distribution of the primary electron beam and the backscattered electrons (Chang, 1975).

Plots of r_0 versus the exposure time are found to be nearly constant functions of the exposure time above 20 s. Therefore, the experimental data of the 100 s exposed points have been chosen to be compared with the theoretical ones.

Heidenreich and Thompson (1973) have described nearly the same characteristics of the disc radii vs. exposure time. The radius r produced by a small incident probe beam and the backscattered electrons has been found to be linear with log t. According to Heidenreich and Thompson, this requires that the backscatter current density at the target surface be of the form

$$J_B(r) = A \exp(-br) \tag{11}$$

The results given in Fig. 4 show a difference between the experimental data and those obtained from the model proposed in this work. The differences result from the fact that the point source was used instead of the real one, because the discrepancy increases as the beam width increases. The plots should be shifted with respect to each other by the beam radius. The measuring of the beam radius is difficult. The diameter within which the current density decreases by a factor of 2 is estimated as $< 1\ \mu m$ for 1 nA current on the basis of the resolution of the scanning image. However, the difference between the experimental data and the theory is greater than that. A structure Si + 0.2 μm Au may be analyzed as an example. For the same exposure time of 100 s, the observed disc radius is 3.3 μm and 3.9 μm for 0.25 nA and 1 nA electron beam current, respectively, while according to the calculations based on the Kanaya and Okayama theory it is 1.97 μm. As an additional effect of a non-point source, the "tails" of the Gaussian distribution of the primary electron beam can be observed. Although the electron current density in the points remote from the beam axis is small, a long exposure may cause degradation of the polymer.

The radial exposure intensity distribution introduced by the point source of electrons which was evaluated experimentally, has been described by Chang (1975). The best approximation has been found as a sum of two Gaussian distributions:

$$C_1 \exp[-(r/B_1)^2] \text{incident primary beam}$$
$$C_2 \exp[-(r/B_2)^2] \text{backscattered electrons} \tag{12}$$

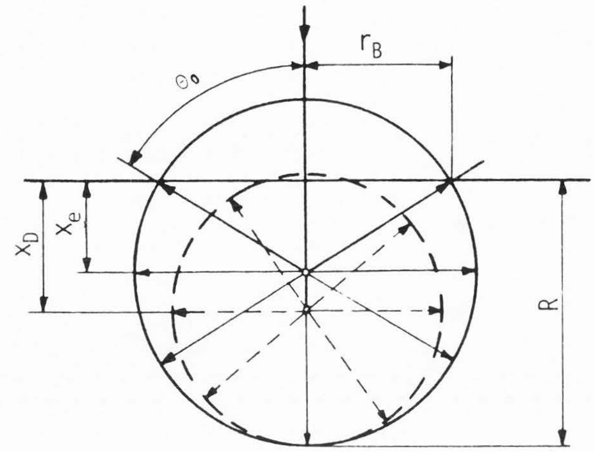

Fig. 1. Diffusion models of electron penetration in targets: dashed line—Archard theory, solid line—Kanaya and Okayama theory.

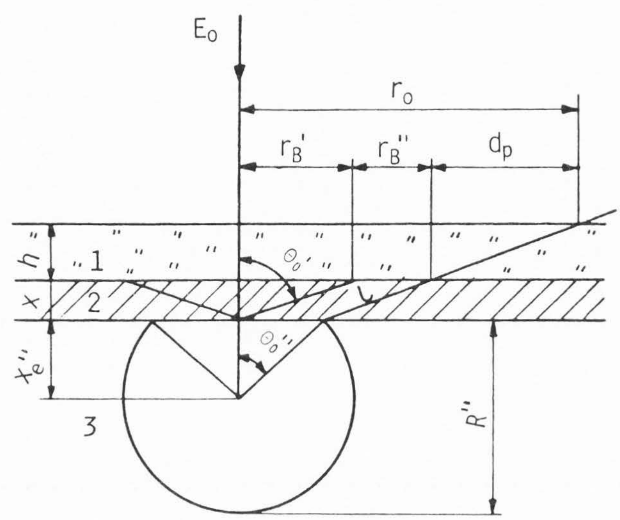

Fig. 2. Simplified model of electron scattering in complex structures. (See text for details.)

Table 1. Theoretical values of r_B', r_B'', d_p and r_0 derived from Archard theory and Kanaya and Okayama theory ($h=0.21\mu m$).

	x [nm]	r_B' [μm]	r_B'' [μm]	d_p [μm]	r_0 [μm]
	0	0	2.68	0.34	3.02
	37	0.23	0.83	1.24	2.30
K and O	73	0.45	0.26	1.24	1.95
theory	120	0.73	0	1.24	1.97
	200	0.73	0	1.24	1.97
	0	0	2.68	0.34	3.02
	37	0.12	1.23	0.66	2.01
Archard	73	0.24	0.68	0.66	1.58
theory	120	0.40	0.26	0.66	1.32
	200	0.63	0	0.66	1.29

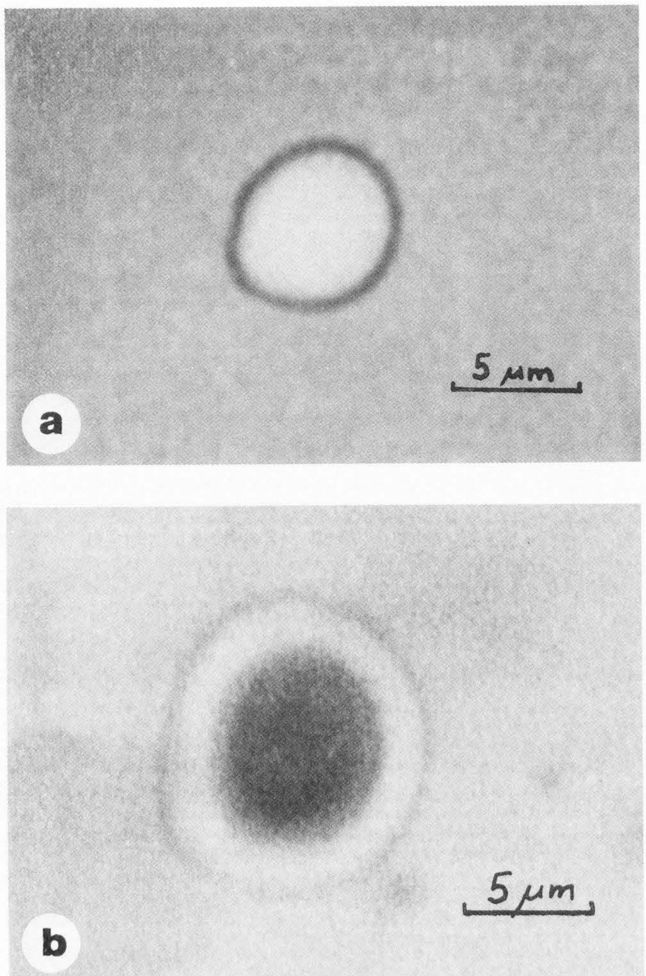

Fig. 3. (a) 2 sec and (b) 100 sec. Backscatter discs of PMMA (h=0.21μm) on Au layer (x=0.12 μm)–Si substrate for different exposure times.

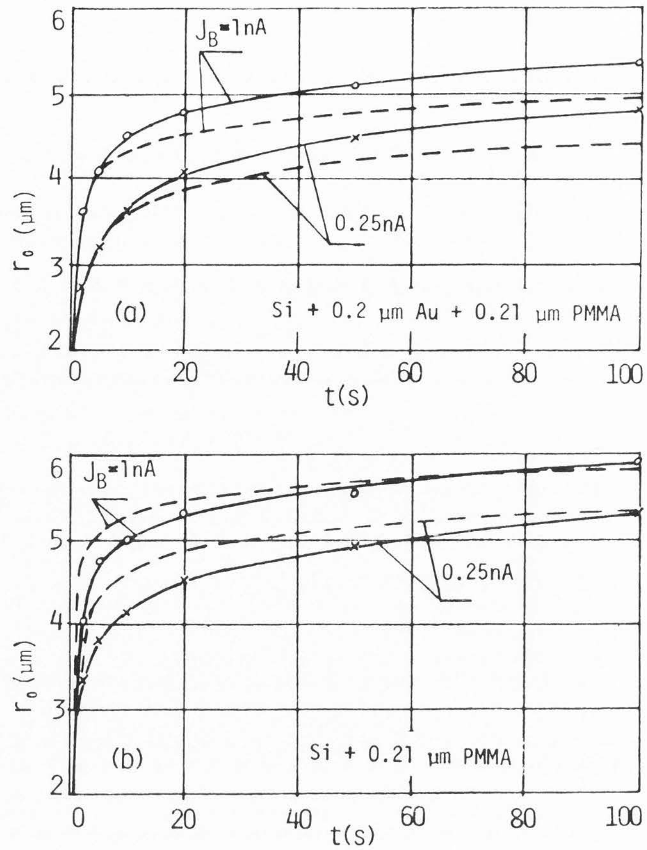

Fig. 4. Exposed disc radius versus exposure time for two structures and for different beam currents (solid line) compared with theoretical results (dashed line).

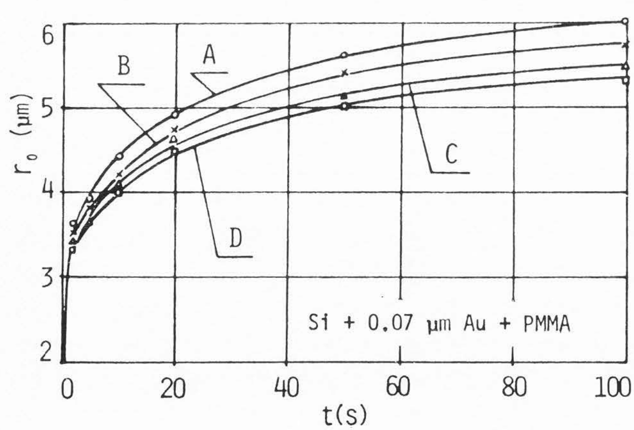

Fig. 5. Exposed disc radius versus exposure time for different PMMA film thicknesses: A=0.25, B=0.22, C=0.18, and D=0.14 μm.

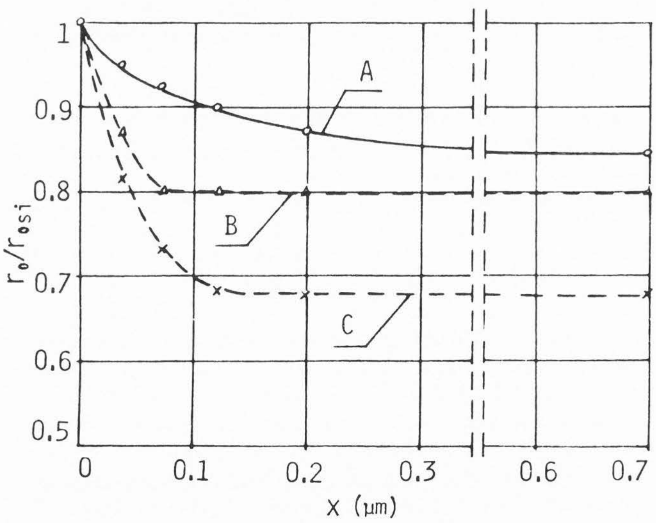

Fig. 6. Exposed disc radius versus Au layer thickness compared with the theoretical calculations based on Kanaya and Okayama theory (Δ) and Archard theory (x).

The results produced by Chang indicate that the zone of the exposure introduced by the backscattered electrons is approximately 2 – 3 μm in radius for 25 keV primary electrons energy.

Let us assume that electron backscattering causes enlarging of the exposure area by a constant value, which is derived from the proposed scattering model. The difference between these data and the experiment is supposed to be caused by the electron beam. This difference is described properly by the Gaussian function proposed by Chang (1975) when $B = 1.1$.

The theoretical radius r_0, enlarged by the effect described by equation (12), is shown as a dashed line in Fig. 4. The discrepancy between these data and the experiment (continuous line) does not exceed 13% for the discussed structures and beam currents. Therefore, the Gaussian distribution adopted into the proposed model seems to properly describe the experimental results.

Si – Au – PMMA structures, differing as to the polymer film thickness, have been exposed in the same way to check the presumption that the backscattered electrons pass through the resist film with no substantial trajectory change, but with the characteristic layer material angle Θ_0'. The results are shown in Fig. 5. According to this assumption, the disc radius should increase by 0.56 μm when the polymer film thickness changes from 0.15 to 0.24 μm. The experiment shows 0.44 μm as a result. This discrepancy can be explained by the limited precision of the measurements.

The dependence of disc radius on the Au layer thickness is shown in Fig. 6. The disc radius diminishes with increasing Au thickness. When the layer reaches 0.2 μm, the radius stabilizes. Such a characteristic agrees with the scattering theory in solids. The substrate influence is negligible when the Au layer is so thick that the electrons are unable to approach the substrate.

According to the diffusion model, in order to observe an effect, the target thickness has to be greater than the dissipation sphere center depth. The Kanaya and Okayama theory states that the depth should be 0.117 μm for gold when the accelerating voltage is 20 keV.

The theoretical plots of disc radius vs. Au layer thickness derived from this model, complete with the beam diameter shift (for 100 s) are shown in Fig. 6. The discrepancy between the theoretical (dashed line) and experimental (solid line) plots for both extreme cases (i.e., Au layers 0.0 and 0.7 μm) is about 10 – 13%. However, the model suggests the radius stabilization at a smaller Au layer thickness in comparison with the experiment.

The experimental plot (Fig. 6) is better approximated by the calculations based on Archard's diffusion model—the radius stabilizes at 0.193 μm of Au for 20 keV. The diminished value of the calculated radius r_0 is obtained as a result. This model is valid only for materials characterized by the atomic number > 40.

The experimental and theoretical data presented are evidence that the proposed simple model is useful in the description of scattering process in complex targets.

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