Numerical Modelling of the Electron Backscattering at the Variable Gas Pressure

M. Krysztof* and W. Słówko

Faculty of Microsystem Electronics and Photonics, Wrocław University of Technology

Janiszewskiego 11/17, 50-372 Wrocław, Poland

The authors prepared a computer programme for simulations of electron flow in various gas conditions. This software combines a commercial programme SIMION 3D v. 7.0, destined for computations of charged particles trajectories in electric and magnetic fields, and the Monte Carlo one written by the authors in the SIMION internal language. The programme takes into consideration the electron scattering in elastic and inelastic collisions, the ionising avalanche and γ processes. This programme was used to investigate the secondary electron backscattering by gas filling the sample chamber of the environmental scanning electron microscope and its influence on the signal to noise ratio S/N and material contrast suppression.

PACS: 41.85.−p, 52.80.Dy

1. Introduction

Variable pressure/environmental scanning electron microscope (VP/E SEM) is commonly used to study insulator specimens or those with high vapour pressure constituents. It overcomes limitations of standard high vacuum SEM thanks to gas filling the sample chamber at the pressure suited to the sample features, while the electron optical column is maintained at high vacuum. These gaseous conditions in the sample chamber are advantageous for the sample itself, but gas disturbs flow of electrons both in the scanning beam and the electron signal generated from the sample, because of frequent elastic and inelastic collisions with gas molecules [1, 2]. There are not many tools for analysis of the charged particle flow in a wide range of gas pressures characteristic of this instrument, i.e. from high vacuum to pressures exceeding 10 hPa. There, electrons and ions go along trajectories shaped both by electric field and collisions of many types, and may produce a cascade of secondary electrons and ions. A solution for the problem may be a computer programme prepared by the authors for simulations of electron flow in various gas conditions. This software combines a commercially available programme SIMION 3D v. 7.0, destined for computations of charged particles trajectories in electric and magnetic fields, and the Monte Carlo one written by the authors in the SIMION internal language [3]. The MC programme takes into consideration the electron scattering in elastic and inelastic collisions but also the ion flow and secondary electron emission stimulated by ion bombardment may be considered, for an inhomogeneous distribution of the gas pressure as well.

The crucial input data defining the events that occur on the unit way and at the unit gas pressure are shown in Fig. 1a and b in the form of diagrams of the electron
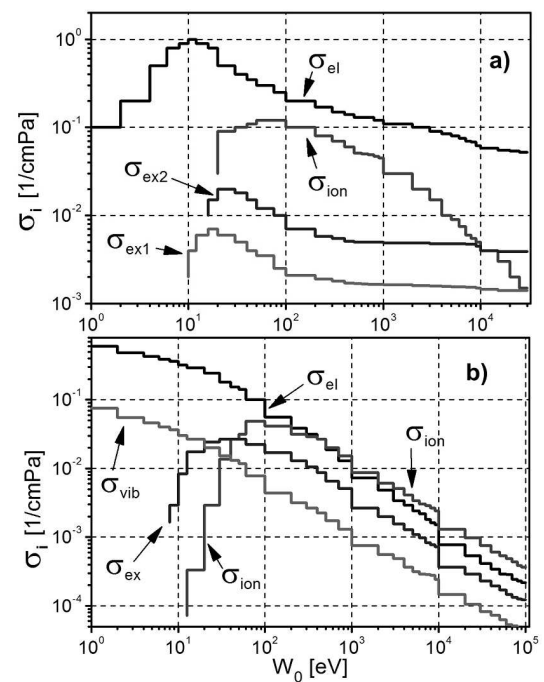

Fig. 1. Electron cross-sections related to the gas pressure for various kinds of collisions at different electron energies in two gases (σ_{el} — elastic c., σ_{ion} — ionisation c., σ_{ex1} — excitation c. I, σ_{ex2} — excitation c. II, σ_{vib} — vibration c., σ_{ex} — excitation c.): (a) argon, (b) water vapour.

cross-sections for various kinds of collisions as functions of electron energies in argon and water vapour [4–6]. At each calculation step (much shorter than the mean free electron path) probabilities of particular events are calculated on these databases and successive events are sampled. In the case of elastic collisions, first the scattering angle is read from the Mott cross-section table and next a rotation angle β in plane normal to the primary direction

* corresponding author; e-mail: michal.krysztof@pwr.wroc.pl

must be sampled to determine the final velocity direction. For the ionisation collision the ionisation energy (16 eV for argon, 12.6 eV for water vapour) is subtracted from the primary electron energy and the rest is divided between the primary and secondary electron. In the case of the excitation collision of a given type the excitation energy is subtracted from the primary electron energy but the direction of the electron velocity remains unchanged.

2. Electron backscattering by gas molecules

In the scanning electron microscopes (SEM) both high vacuum ones and those with sample chambers filled with gas (VP/E SEM), secondary electrons (SE) generated by an electron beam create a main signal carrying information about the sample surface. However, the SE signal may be substantially suppressed by the electron backscattering on gas molecules in the latter instruments. The lost of material contrast in gas is widely known but the backscattering has not been clearly pointed as a main source of the image deterioration because it is always accompanied by many other phenomena which cannot be separated experimentally. So the authors made computer simulations of the electron backscattering effect with the use of the MC-SIMION programme in a flat capacitor model for a row of initial electron energies and electrode bias voltages in the two gases: argon and water vapour.

The results are shown in Fig. 2a and b in a form of diagrams of the electron extraction coefficient τ_e vs. the electron initial energy W_0 at constant values of the free path voltage U_λ. The extraction coefficient τ_e was defined as the number of extracted electrons which can reach the anode (i.e. depleted of the backscattered electrons coming back to the cathode) emitted with a given initial energy $N_e(W_0)$, related to their initial number N_{SE} (200 electrons) at the emission point

$$\tau_e = N_e(W_0)/N_{SE}. \tag{1}$$

The anode bias for particular curves is represented by a so-called free path voltage U_λ defined as a product of the extracting field intensity $E_e = U_a/l_a$ and the electron mean free path λ at an electron initial energy W_0 (i.e. $U_\lambda = \lambda E_e$). The anode of the flat capacitor structure was positioned at the distance $l_a = 100\lambda$ from the cathode, and its bias voltage was taken as $U_a = 100U_\lambda$. The calculations concerned destinations of SEs emitted from the target thus their multiplication in ionising collisions was put off though energy losses in such events were still counted.

The electron backscattering effect consists in the electron initial energy W_0 as a source of the motion, and the high angle elastic scattering of secondary electrons on gas molecules which may turn them back to the cathode. The presence of the extracting field E_e may prevent some electrons from flowing back. Thus, the higher the free path voltage U_λ in comparison to the electron initial energy W_0 is, the lesser electron backscattering and the higher extraction coefficient τ_e becomes. The extracting
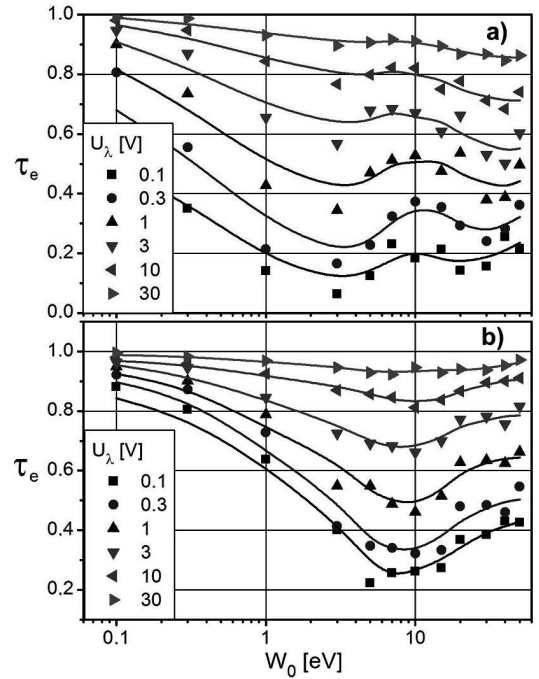

Fig. 2. Extraction coefficient τ_e vs. the electron initial energy W_0 for constant values of the free path voltage U_λ: (a) in argon, (b) in water vapour.

field cannot stop fully the backscattering effect, but energy loss in inelastic collisions may further diminish the electron backscattering and increase the extraction coefficient τ_e. This effect is distinctly seen on the diagrams for argon at low U_λ voltages (Fig. 2a), where local increase of τ_e may be noticed for W_0 close to excitation and ionisation energies (8 eV and 15 eV). Further increase of W_0 results in a drop of the extraction coefficient τ_e because a growing surplus of the initial energy contributes to an increase of the electron backscattering. Diagrams made for water (Fig. 2b) show generally higher levels of extraction coefficients with only one deeper minimum for initial energies below the first excitation. It is so thanks to vibrational excitations which start from very low energies and provide almost constant electron energy loss counterbalancing a relatively high value of the initial cross-section for the elastic scattering.

The general assumption that the numerical model reflects the reality, implies also the opinion that statistical fluctuations of the calculations reflect noise accompanying real processes. Thus, the calculations were conducted for the groups $N_{SE} = 200$ electrons and repeated at least 20 times for every point (trial) which enabled to define the mean number of electrons μ and the standard deviation σ for a chosen group of electrons. So, the data shown in Fig. 3a and b may be interpreted as diagrams of N/S (putting $\sigma/\mu \approx N/S$) vs. the free path voltage U_λ prepared at constant values of the initial energy W_0 for argon and water vapour. The noise level drops rapidly according to an increasing value of the free path voltage U_λ and
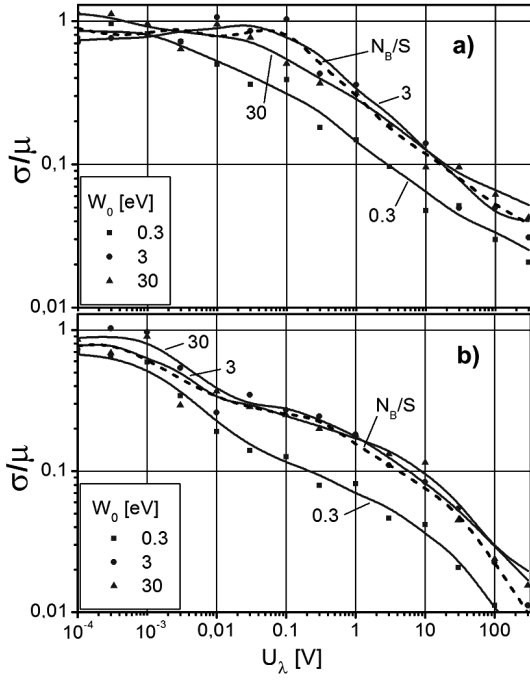
Fig. 3. Relation of the standard deviation to the mean number of electrons reaching the anode σ/μ and N_B/S ratio calculated from (2) for $W_0 = 3$ eV, vs. the free path voltage U_λ taken at constant values of the initial energy W_0: (a) argon, (b) water vapour.

the extraction coefficient τ_e. The backscattering noise results from fluctuations of division of the initial secondary electron current I_{SE} between the extracted current reaching the anode $I_{ae} = \tau_e I_{SE}$, and the backscattered current $I_{BE} = (1 - \tau_e)I_{SE}$, i.e. scattered back to the cathode. Analogously to the multigrid electron tubes where similar distribution noise occurs, the noise to signal ratio may be written as

$$N_B/S \approx k_b (I_{ae} I_{BE}/I_{SE})^{1/2}/I_{ae}$$
$$= k_B (1/\tau_e - 1)^{1/2}, \qquad (2)$$

where k_b and k_B are the noise coefficients. The coefficient k_B can be determined from Figs. 2 and 3. If values of the extraction coefficients τ_e are taken for particular free path voltages U_λ (and chosen initial energies W_0, e.g. 0.3 eV, 3 eV, 30 eV) outcomes of the expression (2) can be compared with the values of the $\sigma/\mu \approx N_B/S$ read in Fig. 3 for these data. As the result $k_B = 0.22$ comes out for argon and 0.2 for water (with less than 3% deviation) at all mentioned energies. The values of $N_B/S \approx f(\tau_e)$ obtained from (2) and converted with use of Fig. 2 to $N_B/S \approx f(U_\lambda)$ at $W_0 = 3$ eV are also shown in Fig. 3.

3. Backscattering and the secondary electron yield

The diagrams of dependence of the secondary electron extraction coefficient τ_e on the electron initial energy W_0

displayed in Fig. 2a, b show rapidly changing values in particular ranges of the energy. It means that the electron backscattering may change not only effective values of the secondary electron yield but also their energy distribution in a process of selective filtering.
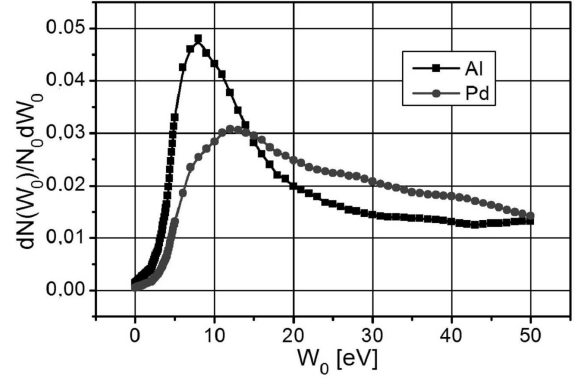

Fig. 4. Initial energy distribution of secondary electrons emitted from Al and Pd normalized by SE yields (areas under curves are unitary) based on [7].

To test this possibility authors prepared the diagrams shown in Fig. 4, concerning the SE initial energy distribution normalized by SE yields (areas under curves are unitary) for Al and Pd, two metals of substantially different densities. The data utilized for these diagrams were taken from [7]. Particular electron energy fractions taken from the diagrams were multiplied by proper values of the extraction coefficients τ_e from Fig. 2. To estimate influence of the backscattering effect on the final contrast of detector signals, the total SE yields should be calculated by integration of the energy distribution curves in the SE energy range.
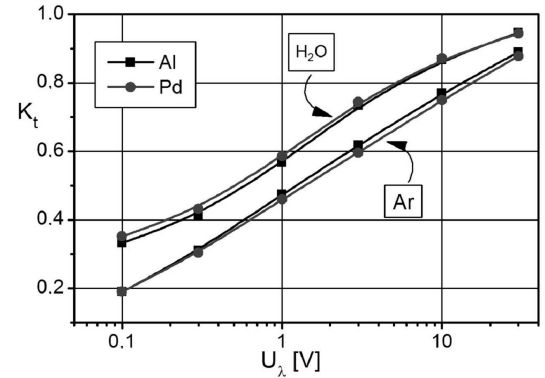

Fig. 5. Total secondary emission suppression coefficient K_t due to the backscattering effect for Al and Pd vs. the free path voltage U_λ: (a) in argon, (b) in water vapour.

The diagrams were initially normalized by the total SE yields from particular targets, so now the integrals shown in Fig. 5 can be interpreted as the total SE emission

suppression coefficients K_B for these targets due to the backscattering effect in argon and water vapour. The SE suppression coefficients observed in Fig. 5 change from the values about 0.95 to 0.2 for lowest extraction voltages (or high pressures). The coefficients are generally higher for water but the diagrams for Pd and Al almost overlay one another, thus secondary emission for these targets is equally suppressed and material contrast between them remains unchanged.

4. Conclusions

The MC-SIMION programme proved to be very useful for analysing complex mechanisms accompanying electron flow in gas. It offers a unique possibility of putting off or on particular phenomena in the computation procedure to investigate their influence on the interesting effect. Now, the most interesting for the authors was the SE backscattering influence on the material contrast in the VP/E SEM. The results were somehow surprising, because the secondary emission for Pd and Al targets were equally suppressed and material contrast between them remained unchanged. In the authors' opinion, such situation results from a specific shape of the initial energy distributions for the targets which cross over at the energy 15 eV defining two equal areas (total SE yields are unitary) where normalized numbers of electrons emitted

from Al are higher ($W_0 < 15$ eV) or lower ($W_0 > 15$ eV) than from Pd. In turn, the diagrams of the extraction coefficient τ_e in Fig. 2 are symmetrical with respect to the energy about 10 eV, too close to the former energy to change balance between the two areas and the mutual material contrast. The contrast will be additionally deteriorated by environmental electrons produced in gas by the primary beam and backscattered electrons emitted from the sample as well as many other noise sources.

References

[1] D.A. Moncreiff, P.R. Barker, V.N.E. Robinson, *J. Phys. D* **4**, 481 (1979).

[2] P. Meredith, A.M. Donald, B.L. Thiel, *Scanning* **18**, 467 (1996).

[3] W. Słówko, M. Krysztof, *J. Microsc.* **237**, 292 (2010).

[4] M. Mitchner, Ch.H. Kruger, *Partially Ionized Gases*, Wiley, New York 1973.

[5] G.N. Rochlin, *Gas-discharge light sources*, Energija, Moskva 1966 (in Russian).

[6] S.M. Pimblott, J.A. LaVerne, A. Mozumder, *J. Phys. Chem.* **100**, 8595 (1996).

[7] D.C. Joy, M.S. Prasad, H.M. Meyer, *J. Microsc.* **215**, 77 (2004).