Improving Secondary Electron Collection Efficiency in Scanning Electron Microscope using Simulation

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1. Introduction

A scanning electron microscope (SEM) is a microscope that images the sample by scanning the surface with an electron beam [1]. The electron beam interacts with the surface and emits various signals containing surface information such as the material's atomic number and depth. Secondary electrons (SE), which are surface-released electrons of energy under 50 eV, are one of the major signals since it provides topographic information [2]. Therefore, collecting clear SE signals is important because it is directly related to the resolution and contrast of the image.

In this research, we used simulation to improve the secondary electron collection efficiency by changing the structure of the collector grid in the secondary electron detector (SED). COMSOL Multiphysics electrostatic study is used for analyzing the system's secondary electron collection efficiency. Experimental data is used to verify the validity of each improvement method.

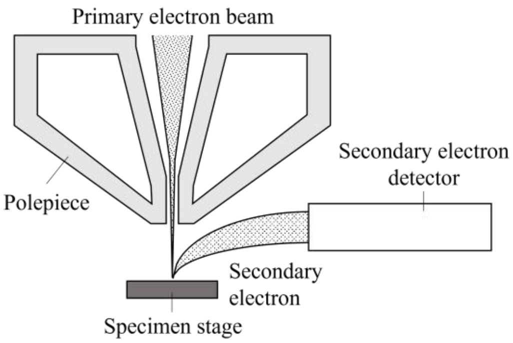

Fig. 1. Schematic of SEM focused on secondary electron detector. Other detector devices such as backscattered electron detector are omitted in this figure.

2. Simulation setup

In this section, basic simulation settings such as bias voltage and distribution of the SE are provided. Some methods to improve the collection efficiency which will be verified in the simulation will also be discussed.

2.1. Secondary electron detector

SEM uses an Everhart-Thornley detector as a SED. Everhart-Thornley detector [3] consists of three parts: collector, scintillator, and photomultiplier.

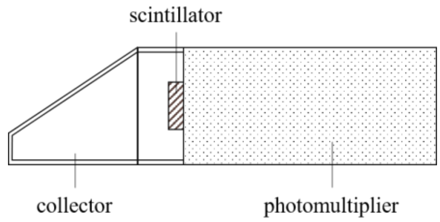

Fig. 2. Schematic of SED in SEM (the left side is toward the specimen). The collector guides SE to the scintillator. The electrons that have reached the scintillator-photomultiplier combination generate current signals.

The collector guides the SE to the scintillator by the positively biased grid. Since the collector grid potential is higher than the specimen, generated SE are accelerated toward the collector grid.

When the SE are guided inside the collector grid, they are accelerated to the highly positive biased scintillator. Scintillator is a material that emits a light signal when an electron collides. This light signal is converted to a current signal and amplified by a photomultiplier. The more electrons are collected by the scintillator, the more current is generated.

In this simulation, the bias voltage of the collector grid is set to +300 V and the bias voltage of the scintillator is set to +6 kV relative to the specimen stage. Also, we assume that the current signals generated by SED are directly proportional to the SE collected by the scintillator. Therefore, secondary electron collection efficiency is determined by the number of electrons gathered by the scintillator in the simulation.

2.2. Secondary electron generation

SE are generated by inelastic collisions between the primary electron beam and the surface material in SEM. Generated SE can be simulated with the electrons with specific energy and angular distribution. The energy of SE is represented as 2-5 eV in most cases [4]. However, the angular distribution of this SE beam differs by each surface material [5]. Therefore, in the simulation, SE are assumed to have uniform angular distribution in the generation area to cover several different angular distributions as much as possible.

In this simulation, the SE generation area is set by a circle with a diameter of 1 mm at the center of the specimen stage. The energy is set to 5 eV. The angular distribution of SE is set to uniform from 0˚ to 90˚.

2.3. Collection efficiency calculation

The collector grid has a mesh grid structure. However, simulating the mesh grid structure is too complicated to implement and requires a long computational time. In the simulation, we replaced a mesh grid structure with a surface that has particle pass-through characteristics. However, in a real mesh grid structure, not all particles can pass the mesh because some particles collide with the mesh wire. Therefore, transparency of the collector grid is applied for more realistic results.

Transparency is a factor that how much particles can pass through the structure. For example, a transparency of 60% means that 60% of particles can pass through the structure. The value of transparency is determined by various reasons such as the material of the structure, geometrical porosity, and electron energy. In this simulation, for simplicity, we use 50% as a collector grid's transparency which is the geometrical porosity of the collector grid mesh.

2.4. Collection efficiency improving method

Since the collector can be modified more easily than other parts in SEM (other parts have more problems in processing or device utilization), we focused on the shape of the collector grid. Modifying the shape of the collector grid changes the electric field line and transparency, which are related to the SE trajectories and the scintillator's net collection. To improve the collection efficiency, the following three factors are applied to the collection grid: length, angle, and transparency.

Extending the collection grid length increases the electric forces exerted on the SE near the specimen. Therefore, the longer the grid gets, the more SE are guided toward the scintillator. In this simulation, the length of the grid is extended from 0 mm to 4.5 mm (extending the grid by more than 4.5 mm causes interference issues); see Fig. 3.

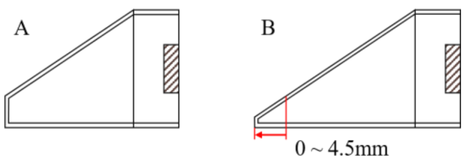

Fig. 3. Figure of extending the collector grid length. The grid length is extended from 0 mm to 4.5 mm (B) compared to the original grid shape (A).

Grid angle is another factor that affects the secondary electron collection efficiency. Since the electron is accelerated along the electric field line, tilting the grid front helps SE accelerate directly to the scintillator. In this simulation, the angle of the grid front is tilted from -15° to 75°; see Fig. 4.

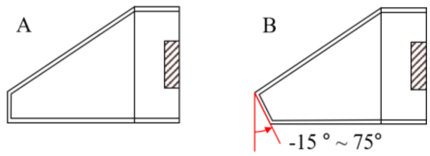

Fig. 4. Figure of tilting the collector grid angle. The grid angle is tilted from -15° to 75° (B) compared to the original grid shape (A). The red direction given is the positive direction.

Net transparency also affects collection efficiency. More electrons can pass the collector grid without disturbing the electric field line by making a partly dense mesh. In this simulation, we partly enhanced the grid transparency to improve collection efficiency; see Fig. 5.

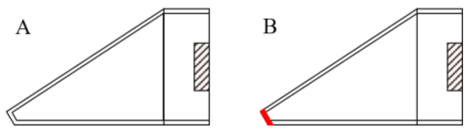

Fig. 5. Figure of partly modifying mesh transparency. We make transparency higher at some positions (B) compared to the original grid (A).

We calculated the collection efficiency enhancement by changing three grid factors (grid length, grid angle, and grid transparency).

3. Result and discussion

As discussed in section 2.4, we calculated the secondary electron collection efficiency with different grid lengths, grid angles, and grid transparencies. Working distance (distance between the polepiece and the specimen stage) is set to 7 mm and 100,000 electrons are used for all simulations.

3.1. Collector grid length

Secondary electron collection efficiencies with different collector grid lengths are shown in Fig. 6 as a black line.

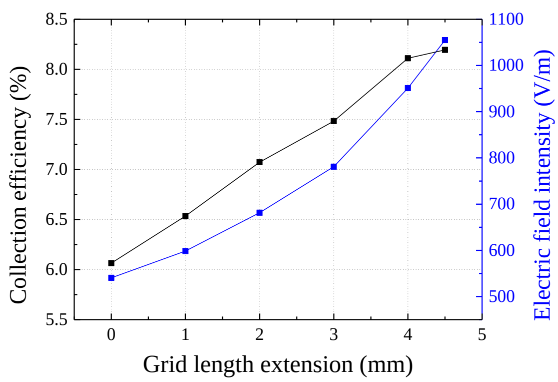

Fig. 6. Secondary electron collection efficiency (black line) and the intensity of the electric field near the specimen (blue line) at different grid lengths. Collection efficiency increases as the collector grid lengthens.

As the grid length increases, the collection efficiency of SE increases. This is because the electric field intensity near the specimen becomes stronger as the grid gets closer to the specimen stage. When the electric field intensity becomes stronger, more generated SE are guided to the collector grid. Therefore, more SE are collected by the scintillator.

3.2. Collector grid angle

Secondary electron collection efficiencies with different collector grid angles are shown in Fig. 7. Also, grid length extension from 0 mm to 4.5 mm and grid angle from -15° to 45° simulation results are shown in Fig. 8.

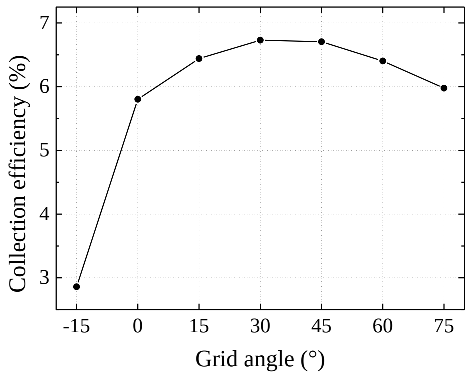

Fig. 7. Secondary electron collection efficiency at different grid angles. Collection efficiency has a peak at the grid angle of 30° with a value of 6.73%.

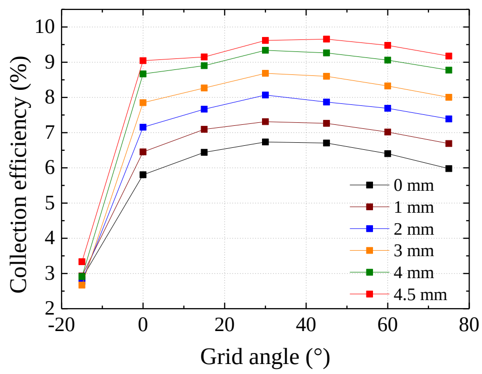

Fig. 8. Secondary electron collection efficiency for all grid angle and grid length domains. Peak value at grid length 4.5 mm and grid angle 45° with the collection efficiency 9.65%.

For the grid angle, there was a tendency to show a peak value between 30° and 45°. The angle of the grid changes the path of electrons by controlling electric field lines. For small angles (< 30°) shown in Fig. 9(a), the electric field formed by the collector grid faces down the grid, making a loss of electrons to the bottom of the grid. Conversely, for large angles (> 45°) shown in Fig. 9(c), the intensity of the electric field at the bottom of the collector is too weak for the collector to sufficiently guide the electrons from the bottom of the grid. At the optimal angle of about 30° to 45° degrees shown in Fig 9(b), the electron from the top of the grid is prevented from falling to the bottom, and the electron from the bottom of the grid is collected by an electric field of appropriate intensity, showing the best collection efficiency.

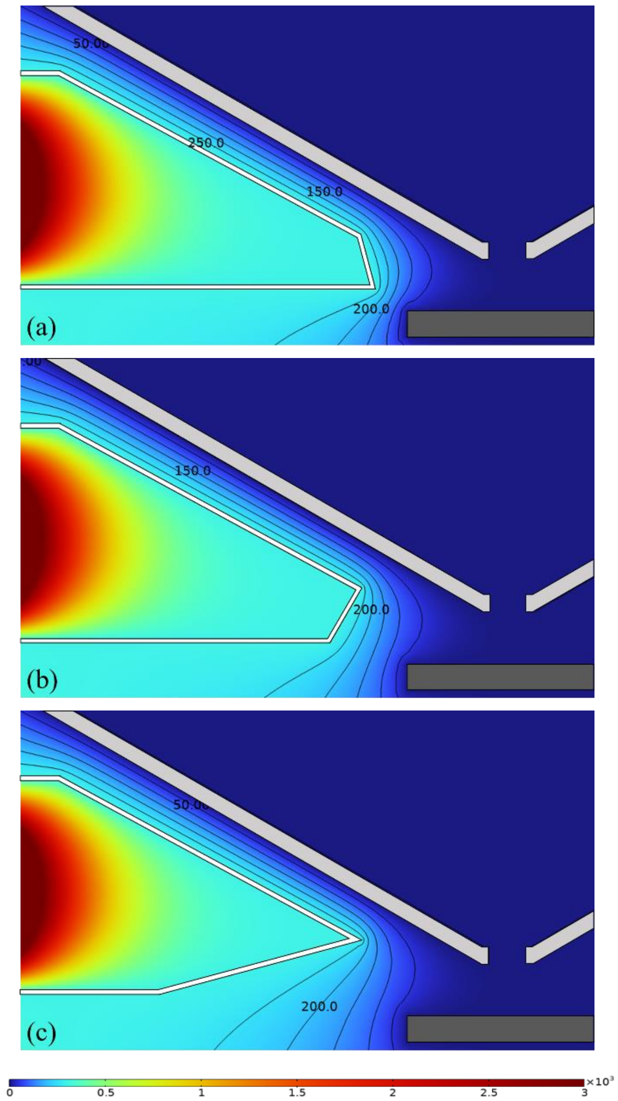

Fig. 9. Electric potential contour at grid angle of -15°(a), 30°(b), 75°(c). The contour shows that the electric field varies with the grid angle.

3.3. Collector grid transparency

Simulations for grid transparency were performed at an angle of 45° and the grid length extension of 4.5 mm, which showed the highest efficiency of 9.66%. As a result of the simulation, when the net transparency of the grid increases to 90.98%, the collection efficiency was 16.46%, showing a 1.7% improvement in collection efficiency compared to the previous one. The collection efficiency is improved by about 2.7 times compared to 6.06%, which was the collection efficiency of the original case of this study.

Table 1: Transparency and collection efficiency by applying transparency modification.

	Best case with grid length, angle	Transparency modification
Net transparency (%)	50	90.98
Collection efficiency (%)	9.66	16.46

3.4. Experimental comparison

We created three collector grids to verify that each of the three methods obtained through simulation is experimentally valid. The information about the three collector grid types is shown in Table 2.

Table 2: Collector grid information used in the experiment.

	TYPE-A	TYPE-B	TYPE-C
Length extension (mm)	0	4.5	0
Tilt angle (°)	45	45	45
Transparency modification	X	X	O

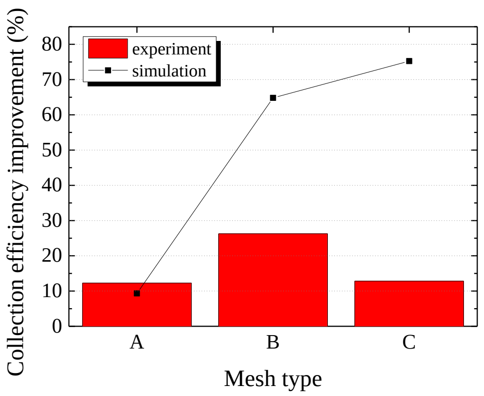

Fig. 10. Experimental data and simulation data comparison. The experiment is performed at a working distance of 5 mm.

The result of comparing the experimental results with the simulation results is shown in Fig. 10. This suggests that the method of improving the secondary electron collection efficiency obtained through simulation can produce significant results in practice.

When comparing the results of TYPE-A and TYPE-C, the effect of the transparency of the grid tended to be overestimated in the simulation compared to the experiment. This is because the transparency of the mesh is greater than its geometric porosity. To obtain more accurate simulation results, it is necessary to measure the transparency of the mesh through extra experiments.

4. Conclusion

Methods for improving the secondary electron collection efficiency through the three modifications of the collector grid were studied using simulation. First, increasing the collector grid length increases collection efficiency by enhancing the intensity of the electric field. Second, tilting the collector grid about 30° to 45° increases collection efficiency by generating a better electric field line to collect SE. Third, increasing the net transparency increases the collection efficiency by reducing the electrons absorbed by the collector grid. Experiments also showed that the simulation provided reasonable results, except for the collection efficiency enhancement by the increment of the net transparency. Experimental data of mesh transparency is required for better simulations.

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