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Effect of Shot Noise and Secondary Emission Noise in Scanning Electron Microscope Images

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Summary: The effect of shot noise and emission noise due to materials that have different emission properties was simulated. Local variations in emission properties affect the overall signal-to-noise ratio (SNR) value of the scanning electron microscope image. In the case in which emission noise is assumed to be absent, the image SNRs for silicon and gold on a black background are identical. This is because only shot noise in the primary beam affects the SNRs, irrespective of the assumed noiseless secondary electron emission or backscattered electron emission processes. The addition of secondary emission noise degrades the SNR. Materials with higher secondary electron yield and backscattering electron yield give rise to higher SNR. For images formed from two types of material, the contrast of the image is lower. The reduction in image signal reduces the overall image SNR. As expected, large differences in δ or η give rise to higher SNR images.

Key words: shot noise, secondary emission noise, Poisson distribution, binomial distribution

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Introduction

There are several processes that deteriorate the signal-to-noise ratio (SNR) of scanning electron microscope (SEM) images—noise in the primary beam, secondary emission noise, and noise in the final detection system. For SEMs with thermionic electron guns, shot noise in the primary beam is the dominant noise source (Dubbeldam 1993). It is a random process arising from the statistical fluctuations in the number of electrons emitted. In addition to shot noise, field emission guns are susceptible to flicker noise. Secondary emission noise is caused by the fluctuation in the number of secondary electrons (SEs) emitted per incident primary electron (PE). Finally, the detection system, typically comprising a scintillator and a photomultiplier tube, contributes further noise sources. However, detection noise is relatively insignificant compared with shot noise and secondary emission noise, provided that the electronic gain is not too high (Dubbeldam 1993).

Noise in the SEM images is a rather difficult issue to handle. The SNR of the images depends on both the beam current and the materials present in the specimen and its topography. Reimer (1998) discussed the emission statistic of SEs and backscattered electrons (BSEs). Dubbeldam (1993) described the characteristics of shot noise, secondary emission noise, and partition noise. It is then important to identify the various sources of noise due to the SEM and their effect on the images.

When the incident primary beam bombards a target material, electrons are emitted in a process called secondary emission. The emitted electrons comprise SEs, BSEs, and Auger electrons (AEs). Secondary electrons can be subdivided into two groups. First, there are the SEs that are excited by the PEs as they enter the specimen. These SEs are usually called SE1 (Drescher *et al.* 1970, Peters 1982). The secondary emission coefficient for these is the SE1 yield, δ_{SE1}. The SE2 yield, δ_{SE2}, is for SEs generated by a BSE as it leaves the specimen (Drescher *et al.* 1970). Since the backscattered yield is η, the total SE emission coefficient δ is given by

$$\delta = \delta_{SE1} + \delta_{SE2} = \delta_0[\sec\phi + \beta(\phi)\eta] \tag{1}$$

where δ_0 denotes the SE1 contribution at normal incidence ($\phi = 0$). Typically β is between 2 to 3 (Reimer 1998).

In this paper, simulations are carried out to study the effect of shot noise and emission noise due to materials that have different emission properties. Since the signal intensity SNR varies locally depending on the material present in the specimen, this has implications on the overall SNR of SEM images. In the simulations, materials with vastly different electron emission properties were selected. Silicon (Si) and gold (Au) are representative of low and high atomic number (Z) elements, respectively. The SE and

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BSE yields of gold are higher than that of silicon. Hence, gold on silicon samples are used to study the noise contribution to the SNR of SEM images.

This paper deals primarily with the SNR of an image as this measures its perceived quality—the signal of an image is represented by contrast modulations within the image. This is opposed to the SNR of the electron intensity detected at a particular point in the image, arising from the statistical fluctuation of various electron emission processes. Hence, for the latter, high signal intensity SNR would be obtained from a featureless specimen if it is irradiated with a large number of PEs, but yet the image SNR of such a specimen would be zero as there is no specimen feature contrast. Nevertheless, clearly the statistical fluctuations of the electron emission processes directly affect the image SNR. We will apply the single image SNR determination method developed by Thong *et al*. (2001) to determine the SNR of the simulated SEM images. Primary electron beam fluctuations and secondary emission noise in the SEM are studied via simulations. Several cases are conducted in the simulations. Before we generate simulated images, we also define some useful parameters that help to describe the various simulation conditions. Finally, the simulation results are compared and discussed.

Simulation of Shot Noise and Emission Noise

The simulation aims to show that the overall SNR of the image is affected not only by shot noise itself, but also by secondary emission noise. An image consisting of 64 × 64 pixels is used for the simulation. Consider first an image where the center 16 × 16 pixels represent an electron-emitting surface (thus as bright as it would appear in an SEM image) and the surrounding area is a nonemitting surface (thus as black as it would appear in an SEM image), as shown in Figure 1. Images of 64 × 64 pixels are used as they require moderate computation time compared with 256 × 256 images; however, the conclusions drawn are without loss of generality.

Each emitting pixel is irradiated by 269 PEs corresponding to beam current at 371 pA and a pixel dwell time of 58.03μs, corresponding to one frame at TV rates (50Hz). The number was a realistic experimental result to simulate the actual condition in the SEM environment.

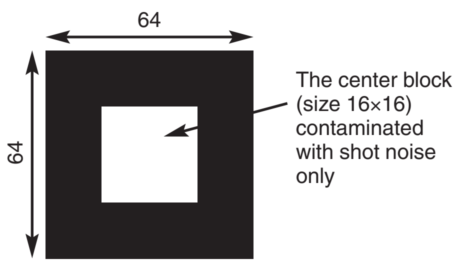

FIG. 1 Image of 64 × 64 pixels with black as surrounding area and the image center with a size of 16 ×16 pixels contaminated with shot noise but no emission noise.

Two different types of material, namely, gold and silicon, are considered. For gold, the total SE yield is 0.26 and the BSE yield is 0.52 at 20 keV primary energy. For silicon, the total SE yield is 0.13 and the BSE yield is 0.18 at 20 keV primary energy. From Eq. (1), the SE1 yield for element gold can be derived as

$$\delta_{SE1,Au} = \delta_{0,Au} \sec \phi_{Au} \tag{2}$$

while the SE2 yield is $\delta_{SE2,Au} = \beta(\phi)_{Au} \eta_{Au} \delta_{0,Au}$ (3)

where δ_{Au} is the SE yield of gold and η_{Au} is the BSE yield of gold.

Similarly, the SE1 yield for element silicon is

$$\delta_{SE1,Si} = \delta_{0,Si} \sec \phi_{Si} \tag{4}$$

while the SE2 yield is $\delta_{SE2,Si} = \beta(\phi)_{si} \eta_{Si} \delta_{0,Si}$ (5)

where δ_{Si} is the SE yield of silicon and η_{Si} is the BSE yield of silicon.

In the simulations, SNR_I, SNR_{II}, and SNR_{III} are three SNR parameters used in this paper: SNR_I is defined as the SNR assuming PE noise is present, but secondary emission noise is absent; SNR_{II} is the SNR of the image formed by SEs; finally, SNR_{III} is defined as SNR of the image formed by BSEs. For SNR_{II} and SNR_{III}, PE noise is always present.

For the simulation, Matlab (Matlab Version 6 Release 12, 2002) is used to simulate both Poisson distributed noise and binomial distributed noise. Three cases are simulated and are addressed in the following sections.

Simulation Cases

To simulate shot noise in the PE beam, the fluctuation in the number of electrons is represented by a Poisson distribution. In addition, it is initially assumed that no noise arises from SE or BSE emission. The first simulation condition is termed Case A.

For Case B, shot noise from the PE is present and, in addition, it is also assumed that emission noise arising from the SE or BSE emission process is present.

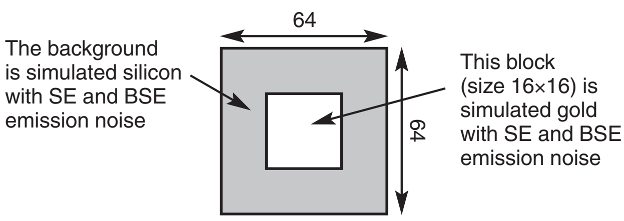

FIG. 2 Case C shows an image of 64 × 64 pixels with silicon as surrounding area. The center block of the image is gold with a size of 16 × 16 pixel. SE=secondary electron, BSE=backscattered electron.

For Case C, a gold-on-silicon sample is simulated. In this case, an image as shown in Figure 2, consisting of 64 × 64 pixels, is studied. The center part represented by 16 × 16 pixels is gold and the surrounding area is silicon. In this simulation, PE shot noise and emission noise are present.

The three cases are summarized in Table I. Some of the key simulation parameters are discussed in the following section.

Generation of Simulated Images

Before we generate simulated images, we need to define some useful parameters that help to describe the various simulation conditions. In general, there exists shot noise in the PEs, and the fluctuation in the PE is represented by a Poisson distribution. If the number of PEs per pixel is $N_{PE}(x,y)$, then

$$N_{PE}(x,y) = \overline{N}_{PE}(x,y) + f(N_{PE}) \tag{6}$$

where $\overline{N}_{PE}(x,y)$ is the mean number of PEs per pixel and $f(N_{PE})$ is the fluctuation in the number of PEs per pixel.

For noise-free secondary electron emission process, we can simulate the number of SEs electrons per pixel without noise as $N_{SE}^{NF}(x,y)$. Hence,

$$N_{SE}^{NF}(x,y) = \delta.(\overline{N}_{PE}(x,y) + f(N_{PE})) = \delta.(N_{PE}(x,y)) \tag{7}$$

where δ is the SE yield. The above equation basically describes that the SE electrons are excited by PEs with a yield of δ.

Similarly, the number of noise-free BSEs per pixel, $N_{BSE}^{NF}(x,y)$, can be simulated as

$$N_{BSE}^{NF}(x,y) = \eta.(\overline{N}_{PE}(x,y) + f(N_{PE})) = \eta.(N_{PE}(x,y)) \tag{8}$$

where η is the BSE emission yield.

TABLE I Various conditions are set to measure the SNR_I, SNR_{II}, and SNR_{III}

Simulation conditions	Case A	Case B	Case C
Description	Center block (simulated gold or silicon) with black surrounding area	Center block (simulated gold or silicon) with black surrounding area	Center block (simulated gold) with simulated silicon as surrounding area
Presence of shot noise	Yes	Yes	Yes
Presence of emission noise	No	Yes	Yes

If there is noise in the SE emission, the number of SEs per pixel is $N_{SE}(x,y)$ and is simulated as

$$\begin{aligned} N_{SE}(x,y) &= (\delta + RV(\delta))(\overline{N}_{PE}(x,y) + f(N_{PE})) \\ &= (\delta + RV(\delta))(N_{PE}(x,y)) \end{aligned} \tag{9}$$

where $RV(\delta)$ is a random variable representing the instantaneous SE yield and whose mean and variance follow a Poisson distribution.

Likewise, the number of BSEs per pixel with emission noise, $N_{BSE}(x,y)$, is simulated as

$$\begin{aligned} N_{BSE}(x,y) &= (\eta + RV(\eta))(\overline{N}_{PE}(x,y) + f(N_{PE})) \\ &= (\eta + RV(\eta))(N_{PE}(x,y)) \end{aligned} \tag{10}$$

where $RV(\eta)$ is the random variable representing the instantaneous BSE yield whose mean and variance values follow a Binomial distribution.

To mimic the process of shot noise, we apply Monte Carlo techniques to generate a Poisson-distributed electron emission for the electron-emitting surface. Since each pixel is irradiated by an average of 269 PEs, the number of PEs in the 16 × 16 pixel region can be described by Eq. (6). This shows that the number of PEs in the center block consists of the mean number of PEs and the random fluctuation in the number of PEs. After that, SNR_I for Cases A and B are calculated using the single image SNR determination method.

For Case A, in which there is no secondary emission noise, the number of PEs in the center is multiplied by δ or η for SE emission or BSE emission, respectively, as shown in Eq. (7) and Eq. (8). For example, the SE yield of gold is 0.26, so the number of PEs in the center 16 × 16 pixel region is then multiplied by $\delta = 0.26$. Similarly, for silicon, the number of PEs in the center region is multiplied by $\delta = 0.13$. Likewise, the number of PEs in the center region is multiplied by $\eta = 0.52$ or $\eta = 0.18$ for gold or silicon BSE emission, respectively. We can then calculate SNR_{II} and SNR_{III} for gold and silicon.

However, for Case B, in which secondary emission noise exists, the mean and variance values of the SE yield are those of a Poisson distribution. Therefore, the number of PEs in the center is multiplied by $\delta + RV(\delta)$ as shown in Eq. (9) for SE emission. Similarly, the number of the PEs in the center is multiplied by $\eta + RV(\eta)$ as shown in Eq. (10), where the BSE emission process is taken into consideration. Again, we can calculate SNR_{II} and SNR_{III} for gold and silicon.

For Case C, in which secondary emission noise exists, we use the same Monte Carlo techniques to generate shot noise according to a Poisson distribution. In the second step, we generate simulated SE and BSE images as follows.

The image where the center is 16 × 16 pixels represents a gold electron-emitting surface and the surrounding area is a silicon electron-emitting surface. The number of PEs in the center is then multiplied by $(\delta_{Au} + RV(\delta_{Au}))$, while the surrounding area is multiplied by$(\delta_{Si} + RV(\delta_{Si}))$, where δ_{Au} is the SE yield of gold and δ_{Si} is the SE yield of silicon. By using the single image SNR determination method, we can calculate SNR_{II} for gold on silicon.

For the BSE signal, the number of PEs in the center region is multiplied by $\eta_{Au} + RV(\eta_{Au})$ and the surrounding area is multiplied by $\eta_{Si} + RV(\eta_{Si})$, where η_{Au} is the BSE yield of gold and η_{Si} is the BSE yield of silicon. We then calculate SNR_{III} for gold on silicon as shown in Figure 2.

Simulation Results and Discussion

Case A

Ten simulations were carried out for each of the Cases A–C. The average value of the 10 simulations was then evaluated. Table II shows the average SNR_I, SNR_{II}, SNR_{III} for gold and silicon; the third column of the table shows the standard deviation of the evaluated SNR; and the fourth column shows the percentage of standard deviation. Note that the simulated results are very close to one another, just as the same set of random numbers used in all cases.

For Case A, only PE shot noise is present. The SNR_I, SNR_{II}, and SNR_{III} for different materials are about the same. The simulated image consists of different materials with different emission properties. However this case assumes no emission noise in the secondary emission process, and hence only shot noise affects the SNR. Although gold has a higher yield than silicon, SNR_I, SNR_{II}, and SNR_{III} are identical irrespective of material, as both signal and noise increase proportionally with δ or η.

However, in reality, emission noise is unavoidable and would affect the SNR. In the next case, we will consider the effect of emission noise contributed from SE and BSE emission.

Case B

An image of 64 × 64 pixels with black surrounding area is studied. The center of this block is contaminated not only by shot noise but also by emission noise.

In this case, both shot and emission noise exist. Therefore, the SNR values in Table III are different and depend on the material. The SNR_{II} and SNR_{III} are smaller than SNR_I due to existence of emission noise. This shows that the emission noise affects the overall SNR value in SEM images. The SNR_{II} and SNR_{III} of gold are higher than that of silicon, as gold has a higher SE and BSE yield than that of silicon.

Table III for Case B yields some important information. In the BSE emission, the signal of gold ($Signal_{Au}$) is the product of α with the signal of silicon ($Signal_{Si}$), where α is the ratio between BSE yield of gold and BSE yield of silicon. However, the noise of gold ($Noise_{Au}$) is the product of ω with the noise of silicon ($Noise_{Si}$), where ω is the ratio between $\sqrt{\mathrm{var}(\overline{N}_{PE}(x,y)\eta_{Au})}$ and $\sqrt{\mathrm{var}(\overline{N}_{PE}(x,y)\eta_{Si})}$, $\mathrm{var}(\overline{N}_{PE}(x,y)\eta_{Au})$ is the variance of the number of BSEs emitted from gold, and $\mathrm{var}(\overline{N}_{PE}(x,y)\eta_{Si})$ is the variance of the number of BSEs emitted from silicon. This shows that $\frac{Signal_{Au}}{Noise_{Au}} > \frac{Signal_{Si}}{Noise_{Si}}$ as $\eta_{Au} > \eta_{Si}$.

The SNR_{III} is proportional to the

$$\frac{\overline{N}_{PE}(x,y)\eta}{\sqrt{\mathrm{var}(\overline{N}_{PE}(x,y)\eta)}}$$

(Reimer 1985), where $var(\overline{N}_{PE}(x,y)\eta)$ is the variance of the number of BSEs emitted from specimen. Similarly, SNR_{II} is proportional to the

$$\frac{\overline{N}_{PE}(x,y)\delta}{\sqrt{\mathrm{var}(\overline{N}_{PE}(x,y)\delta)}}$$

(Reimer 1985), where $var(\overline{N}_{PE}(x,y)\delta)$ is the variance of SE emitted from specimen. For the PEs, SNR_I increases proportional to $\sqrt{N_{PE}}$.

Case C

In this section, an artificial gold on silicon image (64 × 64 pixels) with gold as the center block is studied. The background of the image is silicon. The image is contaminated by both shot and emission noise. The details are shown in Figure 2.

TABLE II SNR_I, SNR_{II}, and SNR_{III} results for gold and silicon in Case A

Components	Average signal-to-noise ratio	Standard deviation	Standard deviation %
SNR_I	13.2	0.18	1.36
SNR_{II} (Au)	13.1	0.16	1.22
SNR_{II} (Si)	13.0	0.17	1.31
SNR_{III} (Au)	13.1	0.19	1.45
SNR_{III} (Si)	13.2	0.15	1.14

TABLE III Signal-to-noise for gold and silicon in Case B

Components	Average of signal-to-noise ratio	Standard deviation	Standard deviation %
SNR_I	13.5	0.19	1.41
SNR_{II} (Au)	10.7	0.31	2.90
SNR_{II} (Si)	9.1	0.42	4.62
SNR_{III} (Au)	12.6	0.27	2.17
SNR_{III} (Si)	10.3	0.41	3.98

TABLE IV SNR_I, SNR_{II}, and SNR_{III} results for gold on silicon specimen in Case C

Components	Average signal-to-noise ratio	Standard deviation	Standard deviation %
SNR_I	6.23	0.15	2.4
SNR_{II}	1.36	0.07	5.4
SNR_{III}	5.26	0.12	2.2

In this simulation, the image contains emission not only from gold but also from silicon. The SNR_{II} and SNR_{III} values in Table IV are lower than the corresponding values in Table III. The main reason is that there is a loss of contrast in the images compared with the images in Case B. In other words, the total signal of the image was reduced. In Case B, we have a signal from the center block and no signal from the surrounding area; therefore, the contrast between the center block and surrounding area is high. This represents the image signal. However, in Case C, there are emissions from two materials in the image. The contrast is smaller than that in Case B. In fact, the image signal is very dependent on the emission properties of the center block and surrounding area.

Another observation from the above table is that $SNR_{III}>SNR_{II}$. This is because the BSE yield is a strong and predictable function of atomic number, unlike the SE yield which has no correlation with Z. We are dealing with images containing emission from two materials: One has high Z and the other has low Z. The large difference in η give rise to high contrast and contribute to high SNR_{III}. On the other hand, both SE yields of gold and silicon are low and comparable; thus the SE image has low contrast and that of SNR_{II} is lower.

Conclusions

We have simulated the effect of shot noise and emission noise corresponding to materials with different emission properties. The local variations in signal and noise due to different emission properties affect the overall SNR value of the SEM images.

In the case in which emission noise is assumed to be absent, the image SNRs for silicon and gold on a blank background are identical. This is because there is only shot noise, and it is assumed that there is no subsequent degradation in the SNR. In practice, both shot and emission noise are present. This addition of secondary emission noise degrades the SNR values. Materials with higher δ or η give rise to higher SNR.

For images formed from two types of material, the contrast of the image is lower. This reduction in contrast reduces the overall SNR. As expected, large differences in δ or η give rise to higher SNR images.

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