Determination of electrons location using mirror effect phenomena in scanning electron microscope

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Abstract. In sense of the phenomena of mirror effects, the behavior of electrons inside the chamber of scanning electron microscope (SEM) investigated. Indeed, a simplified geometrical explanation for the behavior of incident electrons introduced. The presented description is mainly concerns with simple trigonometric functions. However, the synthesis of these functions provide a tool which can be used to trace electron as it leaves the column diaphragm until it reaches the detectors. Accordingly, the position of landing electrons throughout its travel being determinable in terms of the sample potential the operation variables. Results have shown that introduced approach could commendably use to simulate behavior of electrons inside the chamber of SEM.

Keywords: Scanning electron microscope, Trapped charges, Mirror effect, Mirror images, Electron trajectory.

1. Introduction

The scanning electron microscope (SEM) is an important apparatus for imagining, investigating and analyzing of a wide range of materials. Such a device may reveal details around the limits of the nanometer. Indeed, the mechanism that generates the image is the detection of products resulting from the interaction of the primary beam with specimen atoms. Consequently, several number of signals may be generated like backscattered electrons, secondary electrons, X-ray, Auger electrons, cathodoluminescence and specimen current [1].

One of the most crucial problems in operating SEM is the inspection of insulator samples. Several unusual effects appear when such sort of material investigated using SEM and FIB apparatus. These unusual effects conventionally named as mirror effects. Where, an image for the roof of the chamber appears instead of the sample surface. Indeed this type of images, concerning with SEM, called electron mirror images. However, the reason that leads to get such images the ability of insulators to accumulate the charges (electrons and ions). Accumulated charges work as a mirror for the latter incoming electrons. Therefore, these electrons forced to reflect back toward the roof of the chamber. The interaction between the reflected electrons and the roof walls liberates secondary electrons. Detection of secondary electrons leads to form what so called electron mirror images. Phenomenon of mirror images is widely investigated by many authors, see for example [2]; [3]; [4];[5] and [6].
Obviously, the characteristics of mirror images delineate by the behavior of the electrons beam inside the chamber. However, this behavior investigated in terms electron motion [7], charges trapped [8,9], mirror plot curve [10,11], the beam motion [12] and the beam and charging parameters [13].

Presented work aims at investigates the behavior of a charged particles (electrons) beam inside the chamber of SEM by means of mirror effect aspects. A simplified geometrical description for the movements of incident electrons has been introduced.

This trigonometric tool may be used to trace electron as it leaves the column diaphragm until it reaches the detectors. Therefore, the incident electrons coordinates during its travel being locatable in terms of a specific sample potential versus several operation variables.

2. Method

In sense of the mirror effect, the incident electrons undergo a Coulomb’s repulsive force as it being within the range of the sample field. This force mainly depend on the accelerating potential \( V_{sc} \) and the potential of sample surface \( V_s \). Consequently, at the distance when \( V_s \) become equal to \( V_{sc} \) these electrons reflected back, toward different point at the upper ceiling chamber. Figure.1 shows a simplified diagram that reveals such process in terms the incident angle \( \theta \), scattering angle \( \beta \), radius of the irradiated area \( R \) and the working distance \( W \). Actually, the incident electron leaves the column diaphragm at the point \( A \) orienting in the direction of the sample. Such electron suffers a reflection at the point \( B \) where its kinetic energy vanishes due to \( V_s \), and finally the electron reaches the chamber upper wall at the point \( L \).

Indeed, the trace of vertical height (\( BC \)), at which an incident electron reflects back, along with the variation of \( \theta \) draws the real equipotential surface in sense of Gauss’s law. Therefore, one may determine the actual surface where the incident electron stopped, and then reflected back, by the sample potential. However, to reach this task the following procedure may follows.

![Figure 1: A schematic diagram for an incident electron inside a chamber of SEM in sense of mirror effect phenomena.](image-url)
First of all, let consider that the irradiated area is a circle of radius $R=OF$, so the angle $\theta$, where the incident electron ray asymptote intersect the border of an irradiated area, can assigned to be:

$$\theta = \tan^{-1}\left(\frac{R}{W}\right) \quad \cdots \cdots (1)$$

Obviously, values of incident angle greater than that specified by equation (1) gradually fails to reflecting back and eventually hit sample areas where trapped charges being absent. Figure .1 clearly shows that the vertical distance ($BC$) can evaluate as in the following formula:

$$BC = \frac{CF}{\tan \theta} \quad \cdots \cdots (2)$$

Since the incident angle is determined by mean of equation (1), the next problem is to find the segment $CF$. According to equation (1) and the following relation:

$$OC = y_B \sin (\alpha - \theta) \quad \cdots \cdots (3)$$

One can easily deduce the expression for $CF$ to be as in the formula below;

$$CF = W \tan \theta - y_B \sin (\alpha - \theta) \quad \cdots \cdots (4)$$

Where the angle $\alpha$ can be evaluate according to the following formula;

$$\alpha = \sin^{-1}\left(\frac{w \sin \theta}{y_B}\right) \quad \cdots \cdots (5)$$

Therefore, the vertical distance become;

$$BC = W - \frac{y_B \sin (\alpha - \theta)}{\tan \theta} \quad \cdots \cdots (6)$$

Where the symbol $y_B \equiv OB \equiv OP$ refer to the radius of the Gaussian surface arises according the way by means the trapped charges are accumulated. Almost, equation (6) can be adopted to form the actual potential surface, at which the incident electrons reflects back, and hence the coordinates of the reflection point can be defined. Obviously, figure 1 reveals that the scattering angle may easily evaluated as $\beta = 180 - 2\alpha$.

In order to use equation (6) the radius $y_B$ should be define first and so the sample surface potential function must be determined. Throughout this work the following expression is adopted [Abbood 2010];

$$V_s(y) = \frac{2Q_t}{4\pi \varepsilon_0 R^2} \left[ (y^2 + R^2)^{1/2} - y \right] \quad \cdots \cdots (7)$$

Equation (7) describe the potential along the distance $y$ that is vertical to disk area of radius $R$ comprise a trapped charges of amount $Q$. However, this potential is suggests to be determine inside the chamber of SEM, which is a free space of permittivity $\varepsilon_0$. It is worth to mention that, the vertical distance at the reflection point ($B$) appear in figure .1, i.e. $y_B$ can be evaluated by means of the last equation to be;

$$y_B = \frac{R(\alpha^2 - \lambda^2)}{2\lambda Q_t^2} \quad \cdots \cdots (8)$$

Where $\lambda$ represent the quantity $2\pi Re_0 V_{sc}$. Therefore, the procedure steps have now been complete and for a specific area of irradiation and well-defined trapped charges, the sample potential along the interval between sample diaphragm can be define. Thereafter, the radius of equipotential surface $y_B$ can evaluated with aid of the formula (8). Hence, equation (6) being applicable to determines the actual Gaussian’s surface.
3. Results and discussion

In order to implement the procedure presented in last section the QUANTA-200 3D dual beam machine has been used. The Polyethylene Terephthalate (PET) material used to prepare the samples required to perform the work experiments. The PET samples have perpetrated to be of a flat shape circle of diameter 1 cm and 1.5 mm thick so as to be suitable to hold at the chamber stage. The measured dielectric constant of the used PET sample is 3.43 obtained at frequency 1 MHz. Surface of PET samples was cleaned using distilled water. Experiments carried out at room temperature and pressure of 2.0x10^{-5} Pa. The working distance W maintained fixed to the value 15 mm. The sample irradiated with a potential 30 kV in a scanning mode (32 frames) over an area of 0.2826 mm² with radius R=0.3 mm for 5 min. The measured trapped charges was 0.3 nC. Thereafter an electron mirror images received with a scanning potential values 1, 2 and 3 kV respectively.

Figure 2 shows the variation of sample potential along the working distance. It is seen that the incident electron suffers a little bit repulsive force near the column diaphragm. However, this force increases gradually as the electron progresses toward the sample. Indeed, at distances less than 2 mm, approximately, the force increases sharply until it reaches about 18.6 kV neighbor the sample surface.

![Figure 2: The variation of surface potential along the working distance for the irradiated sample.](image)

The variation of the vertical distance $y_B$ versus the adopted values of scanning potential are plotted in figure 3. Accordingly, the most important result that may record is that, whenever the electron mirror image being receive by higher potential, the incident electron being closer to the sample. In other word, the incident electron reflecting back at a point closer to the sample as higher values of scanning potential is used. Therefore, more details about the SEM chamber could be obtained as the electron image captured by higher potential.
Figure 3: The variation of vertical distance $y_B$ as a function of scanning potential.

Figure 4 reveals the correlation between incident angle and its counterpart scattering one for different values of scanning potential. It is obvious that, scattering angle decreases gently with increasing of incident angle. Furthermore, such smooth behavior becomes gradually sharp as the electron mirror captured at high potential. Consequently, the angle between the incident and reflected electrons get diverges as shown in figure 5. However, this differ being more apparent when scanning potential increases. Anyway, this definitely indicate that an image of more details for the SEM chamber roof may obtained as long as the incident angle increased.
**Figure 4:** The variation of scattering angle versus the incident one for various scanning potential.

![Graph showing the variation of scattering angle versus the incident angle for different scanning potentials.]

**Figure 5:** The relation between the angles $2\alpha$ and the incident for different values of scanning potential.

Figure 6 shows the variation of the vertical distance where incident electrons reflected as a function of the incident angle. In fact, this relation plot the actual equipotential surface rather the supposed one (i.e. $y_B$) and so, that refer to the real accumulation profile of the trapped electrons. It is important to mention that, as the incident angle increases the vertical distance ($y_B$) get a little bet decreases. Although this behavior is obvious for low scanning potential, one conclude that it is similar for higher values of $V_{sc}$ and hence needs long range of $\theta$ to be significant.

![Graph showing the variation of the vertical distance versus the incident angle for different scanning potentials.]

$V_{sc} = 1$ kV  
$V_{sc} = 2$ kV  
$V_{sc} = 3$ kV
Figure 6: The actual potential surfaces as a function of the incident angle for different scanning potential.

Now, by defining the point $A (O, W)$ where the incident electron leave the column diaphragm, the scattering point $B (OC, BC)$ and the point $C (AL, W)$, where the electron hit chamber roof, the trajectory of such electron can be determined. However, these trajectories for various incident angles at the scanning potential 1, 2 and 3 kV are plotted in figures 7, 8 and 9 respectively. The electron mirror image corresponds to each of these three results are presented also for comparison purposes.

Indeed, mainly two important remarks can be recorded by exploring these three figures. First of them, is that when electron incident with high angle the image field of view being wide and so large area may captured. Obviously, the increases in $\theta$ makes the electron scattered with low value of the angle $\beta$. Hence, the point $B$ of such electron be far away from the optical axes for each operated $V_{sc}$. However, this result being in consistence with that argued for figure 5.

The second remark, in fact, is that the incident electron approaches more and more form the sample as the scanning potential increases. This is an expected result since the higher values of $V_{sc}$ grand the incident electrons a possibility to further penetration inside region of the sample potential. i.e. the kinetic energy of the incident electron become of weight higher that its counterpart potential energy. Due to that, the point $B$ become closes to the sample surface and consequently $\beta$ decreases. Thereby, the point $B$, at the time when it being nearer to the sample, it also become further away from the optical axes as the scanning potential increased. Subsequently, the field of view for the captured electron images being wider as scanning potential increases, see table-I.

Figure 7: (a) The trajectory of the incident electron for various incident angle at scanning potential 1 kV and (b) Its own electron mirror image.
Figure 8: (a) The trajectory of the incident electron for various incident angle at scanning potential 2 kV and (b) Its own electron mirror image.

Figure 9: (a) The trajectory of the incident electron for various incident angle at scanning potential 3 kV and (b) Its own electron mirror image.
Table-I: The axial distance of the point B and its corresponding area for various incident angle at different scanning potential.

| Θ (degree) | $V_{sc}=1$ kV | $V_{sc}=2$ kV | $V_{sc}=3$ kV |
|-----------|----------------|----------------|----------------|
|           | AL (mm) | Area (mm$^2$) | AL (mm) | Area (mm$^2$) | AL (mm) | Area (mm$^2$) |
| 0.1       | 0.2395   | 0.1801        | 0.5372   | 0.9061        | 0.8466   | 2.2505        |
| 0.3       | 0.7194   | 1.6251        | 1.6185   | 8.2253        | 2.5662   | 20.6781       |
| 0.5       | 1.2012   | 4.5306        | 2.7207   | 23.2429       | 4.3677   | 59.9011       |
| 0.7       | 1.6865   | 8.9310        | 3.8592   | 46.7653       | 6.3189   | 125.0859      |
| 0.9       | 2.1767   | 14.8773       | 5.0514   | 80.1222       | 8.5116   | 227.4846      |
| 1.1       | 2.6732   | 22.4384       | 6.0553   | 115.1333      | 11.0834  | 385.7231      |

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References

[1] Hafner B 2007 Scanning Electron Microscopy, Primer University of Minnesota.

[2] Belhaj M, Jbar a O, Filippov M, Rau E, and Andrianov M 2011 Analysis of two methods of measurement of surface potential of insulators in SEM: electron spectroscopy and X-ray spectroscopy methods Appl. Surf. Sci., 177, 58-64.

[3] Milani M, Abdul-Wahab H, Abbood T, Savoia C and Tatti F 2010 Rear window: looking at charged particles hitting a charged target in a FIB/SEM Microscopy: Science, Technology, Applications and Education, 1741-1748

[4] T. Abbood T 2010 Formal Invedtigation of the Mirror Effect in SEM PhD. Thesis: College of Education, University of Al-Mustansiriyah, Baghdad, Iraq.

[5] Al-Obaidi H 2015 Beam analysis of scanning electron microscope according to the mirror effect phenomenon J. Electrostatics, 74, 102–107.

[6] Croccolo, F and Riccardi, C 2008 Observation of the ion-mirror effect during microscopy of insulating materials J. Microsc., 229, Pt 1, 39-44.

[7] Vallayer B., Blaise G, and Treheux D 1999 Space charge measurement in a dielectric material after irradiation with a 30 kV electron beam: Application to single-crystals oxide trapping properties Rev. Sci. Instr., 70, No. 7, 3102-3112.

[8] Wintle H 1999 Analysis of the scanning electron microscope mirror method for studying space charge in insulators J. Appl. Phys., 86, No. 11, 5961.

[9] Abbood T, Hadi H, Karim M and Mohi A 2016 Determination of Accumulated Electrons at PET Surface Using Mirror Effect Phenomena in SEM J. World Sci. N. 55,27-37.

[10] Ghorbel N, Kallel A, Damamme G, Renoud R, Fakhfakh Z. 2007 Analytical description of mirror plot in insulating target Eur. Phys. J. Appl. Phys. 36, 271–279.

[11] Al-Obaidi H, Mahdi A and Khaleel I 2018 Characterization of Trapped Charges Distribution in Terms of Mirror Plot Curve Ultramicroscopy, 184, 12-18.
[12] Al-Obaidi H and Khaleel 2013 The beam current considerations in SEM accordance to mirror effect phenomenon,  *J. Int. Lett. Chem. Phys. Astron.* **10**, 70–75.

[13] Al-zahy Y 2015 Differential cross section for reflected electrons measured by electron mirror method, *J. of Nanophotonic*, **9**, 1-14.

[14] Ronak Ali et al 2020 J. Phys.: Conf. Ser. 1530 012156.