Journal of Engineering and Applied Sciences 13 (Special Issue 14): 10962-10966, 2018
ISSN: 1816-949X


# Estimation the Required Beam Current to Eliminate the Mirror Effect

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**Abstract:** This research studies the distribution of the restricted ion on the surface of the sample (PMMA) Poly-Methyl Methacrylate by irradiating it with an ion beam inside Focusing Ion Beam device (FIB). Using the charged disc approach, the mathematical description for the process of charging restricted ions on the surface of the sample has been provided. Although, the theoretical formulation has been provided depending on simple ideas of electricity, however, it provided fairly consistent results with practical results. In the current work, a theoretical relationship was derived to help researchers overcome the mirror effect for the first time.

**Key words:** Charge effect, trapped charge on dielectric surface, ion beam current, ion mirror phenomenon, insulator charging, disc

## INTRODUCTION

The Scanning Electron Microscopy (SEM) and Focusing Ion Beam (FIB) have used in the wide field in the many of research field and industrial products. Whereas they considered strong tools to analysis the result and explore microscopic properties which offer information about surfaces of many different model with nanometer dimension (Croccolo and Riccardi, 2008).

The imaging process by using Scanning Electron Microscopy (SEM) and (FIB) is resulting from detecting the secondary electrons caused by the interaction of the elementary electrons with the sample atoms.

Electron mirror effect is observed when the insulator in (SEM/FIB) is used and it's first observed by Clarke and Stuart (1970) and later it's observed by Shaffner and Van Veld (1971) whereas a big effort is done by scientist to prove that phenomenon doesn't occur because it was considered not worthy and it was called Psuedo-Mirror effect. As for Ion Mirror Effect (IME), it was observed by Croccolo and Riccardi (2008). When the phenomenon appeared 40 years ago, many scientist were studying this phenomenon and the idea of ion or electron mirror is simply shows that the incident ions or electrons beam on the insulator surface will be collected on the surface until the surface become full of charges and become as a mirror that reflected the electrons that incident on the model due to coulomb force. In order to create electron or ion mirror; the sample must be dielectric to avoid leakage of charges, the sample that must be isolated from the chamber that must be in vacuum to avoid dispersion and absorption of electrons or ions (Zoory, 2013).

## MATERIALS AND METHODS

### Theoretical and fundamental features

**The physics of charging dielectrics:** The materials that don't conduct electricity and have the ability to store electric charge called dielectric (Rau *et al*., 2008). The study of dielectric samples by using (SEM) and (FIB) are effected as called "charge effect".

Recently, the phenomenon of charging and discharging the dielectrics is attracted much emphasis because of its importance in technology and industry. The study of phenomenon during the storage of the charge on the sample surface is very necessary to explain the force and breakdown the dielectric (Chen *et al*., 1994). Therefore, it is necessary to determine the restricted charge on dielectric surface and study the mobility of the restricted and unrestricted charges integrally (Fakhfakh *et al*., 2004).

When the surface of any dielectric sample is exposed to a beam of ions or electrons, these incoming ions or electrons can be trapped on this surface and later can be detrapped. For a further understanding of the behavior of charging and discharging of dielectrics, the total trapped charge on the dielectric surface, the charge's spatial distribution, the characteristics of the basic factors of charge conservation process, the charges transportation and the breakdown effect should be determined (Chen *et al*., 1995).

So, there are several experimental techniques to measure the total charge and its distribution in dielectric all are referred by Bai *et al*., (1999), Vallayer *et al*. (1999), Wintle (1997) and Fakhfakh *et al*. (2002). This work used mirror method among those experimental techniques.

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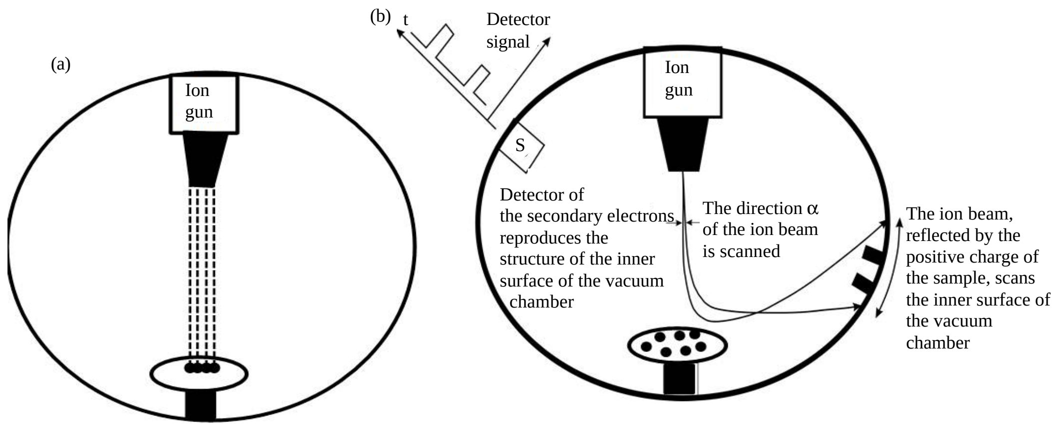


Fig. 1a): A schematic representation showing the charge of the dielectric surface (forming a layer of ions on the sample surface (trapped charge) and b) A Schematic diagram of the ion mirror phenomenon (Zoory, 2017)

**Ion mirror phenomenon:** As mentioned previously that the mirror effect occurred on the isolated surface when a charge is located on this surface and the surface is imaged at a less potential than the potential on dielectric sample surface. When the ion's potential which approaches the charged surface is low, the repulsion force increases between incident and trapped ions during the process of charging surface and this causes changing of incident ion's path, sending it to (FIB) wall. The ions that collide with the inner wall of (FIB) are possibly generates secondary electrons, have properties depend on the wall material and the incident ion's energy. So, the inner part of chamber tends to be imaged as shown in the following diagram (Zoory, 2017) (Fig. 1).

**Disc charge approximation:** The principle study of physics shows that the potential of electricity associated with finding of electric charge. Some of potential properties depend mainly on charge magnitude, general distribution of charges and the distance between centre of this distribution and the point that need potential to be measured for it. According to that, the electrical potential that associated to the trapped charge should be determined in order to understand the behavior of scanning beam of ions. A model was proposed in this paper to represent the trapped charge distribution or represent the associated potential for this charge. The simplest model that could be done is disc charge approximation.

The following expressions represent the sample potential and the potential of the ions beam, respectively (Zoory and Abid, 2018):

$$\therefore \Phi_s(Z) = \frac{Q_t}{2\pi R_s^2 \varepsilon_0 \left[\sqrt{Z^2 + R_s^2} - Z\right]} \qquad (1)$$

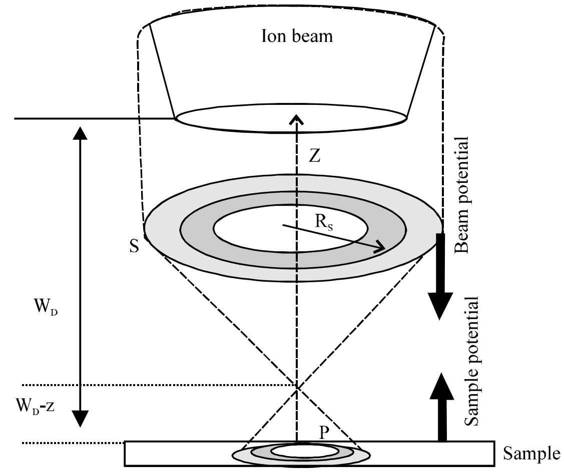


Fig. 2: Schematic illustration for beam of ions incidents on irradiated sample

$$\Phi_b(W_D - Z) = \frac{I_b t}{2\pi R_b^2 \varepsilon_0 \left[\sqrt{(W_D - Z)^2 + R_b^2} - (W_D - Z)\right]} \qquad (2)$$

Where

$(\varepsilon_0)$ = Permittivity in vacuum
$(Z)$ = Length of the optical axis from ion gun aperture to sample surface
$(Q_t)$ = Trapped charge on the surface through a disk of Radius ($R_s$) because of irradiation process
$(I_b)$ = The current of ion beam is a number of charges ($Q_b$) (which forms the surface of the beam) that passing through any point along the beam moves the distance in the unit time (t)
$(R_b)$ = The Radius of the beam
$(W_D)$ = Work distance (Fig. 2)

**Energy conservation law:** It is clearly that Eq. 1 represents the resistance potential which tries to prevent the scanning ions from reaching the sample surface. More precisely, there is Coulomb force which its magnitude is (-egrad $\Phi_s$ (Z)), on the incident ion and thus, it resist them to reach the sample. On the other hand, Eq. 2 shows another Coulomb force of magnitude (-egrad $\Phi_b$ ($W_D$-Z) which tries to weaken the first and push the incident ions away from the aperture of (FIB). In the normal operation of (FIB), the scanning beam of accelerated ions with a specific Voltage ($V_{sc}$) to make the ions interact according to any of the atomic traditional reactions and depending on the values of the acceleration voltage. In this case, the scanning ions acquire additional reasons to be more closed to the sample.

As a result when the total ($V_{sc}$) and ion beam potential ($\Phi_b$ ($W_D$-Z)) is equal to the sample potential ($\Phi_s$ (Z)), the incident ions will stop moving at a certain point on $Z_r$ axis and for this reason they moved toward (FIB) wall chamber. From mirror phenomenon point of view, these ions usually reflect at a point in a vacuumed region. Thus, energy conservation law in reflection point is given in the following relation (Zoory and Abid, 2018):

$$\frac{Q_t}{2\pi R_s^2 \varepsilon_0} = \left[\sqrt{Z^2 + R_s^2} - Z\right] - \frac{I_b t}{2\pi R_b^2 \varepsilon_0}\left[\sqrt{(W_D - Z)^2 + R_b^2} - (W_D - Z)\right] = V_{sc} \tag{3}$$

Equation 3 shows clearly that the balance in Coulomb force is removed to take advantage of ion beam values that depend on the Radius ($R_b$), the current ($I_b$) and the scanning Voltage ($V_{sc}$) in addition to the trapped charges and the radius of charge disc ($R_s$).

## RESULTS AND DISCUSSION

This study is devoted to study ion beam current parameter to dispose of ion mirror phenomenon depending on (PMMA) sample and experimental results by Zoory (2014). The magnitude of ($R_s$) was (0.457 mm = $R_b$) and ($W_D$ = 30 mm) and these values were constants during the study.

**Study of the sample potential ($\phi_s$) and ion beam potential ($\phi_b$):** Figure 3 shows that the value of the sample potential ($\Phi_s$) is high at the model. This value begins to decrease as the distance from the model increases. Figure 3 shows also the changing of ion beam potential ($\Phi_b$) used for imaging mirror phenomenon along the optical axis-Z. whereas ($\Phi_b$) decreases as the distance from coulomb aperture increases (toward sample surface). The intersection points, between these potentials ($\Phi_s$) and ($\Phi_b$) of different imaging currents are the inversion points, i.e., these points represent the maximum distance reached by ion beam before its recoil as a result of the sample potential. Figure 3 shows also when the ion beam current increases as it approaches more from the sample.

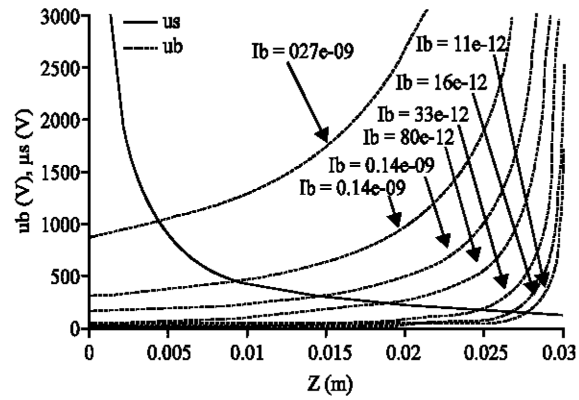


Fig. 3: Variation of the sample potential ($\Phi_s$) and ions beam potential ($\Phi_b$) for different beam currents with energy $V_s$ = 6 kV and along the optical axis

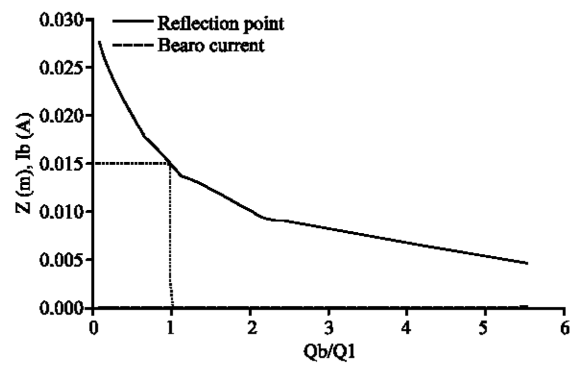


Fig. 4: Variation of the between inversion points (Z (m)) and currents beam (Ib(A)) with (Qb/ Qs)

However, for more clarification, Fig. 4 shows inversion points for different ion beam currents at scanning voltage ($V_s$ = 6 kV). It is clear that when ($Q_t$ = $Q_b$)- the charge on the sample is equal to the charge caused by ion beam ($Q_b/Q_t \approx 1$)-the inversion point will be at distance (15 mm) which represent the half value of work distance ($W_D$ = 30 mm).

**The calculation of the ion beam current:** The results that obtained can be used to avoid the mirror phenomenon which occurs when ($Q_t = Q_b = I_b t$) and ($R_s = R_b = R$). Now it is possible to rewrite the sample potential and the surface potential as following.

Table 1: A comparison between the results of ion beam current by using Eq. 13 and previously published results

| | Experimental (Zoory, 2014) | Zoory and Abid (2018) | Present work Eq. 13 $I_{b1}$ (nA) | | |
|---|---|---|---|---|---|
| $V_{sc}$ (kV) | $I_{b1}$ (nA) | $I_{b1}$ (nA) | t = 1 sec | t = 2 sec | Average time |
| 6 | 0.14 | ≈0.12 | ≈0.150 | ≈0.080 | ≈0.115 |
| 7 | 0.16 | ≈0.12 | ≈0.178 | ≈0.089 | ≈0.134 |
| 8 | 0.17 | ≈0.13 | ≈0.203 | ≈0.102 | ≈0.153 |
| 9 | 0.19 | ≈0.14 | ≈0.229 | ≈0.114 | ≈0.172 |
| 10 | 0.21 | ≈0.14 | ≈0.254 | ≈0.127 | ≈0.191 |

**The sample potential:** When compensating the condition of the mirror phenomenon absence in the surface potential equation, Eq. 1 becomes:

$$\Phi_s(Z) = \frac{I_b t}{2\pi R^2 \varepsilon_0 \left[\sqrt{Z^2 + R^2} - Z\right]} \tag{4}$$

As (R>>Z), i.e., (Z≈0), Eq. 4 will be:

$$\Phi_s(Z) = \frac{I_b t}{2\pi \varepsilon_0 R} \tag{5}$$

**The sample potential:** When the ion beam current increases, the ions become close to ion beam surface that means (Z≈0) and it is possible to rewrite Eq. 2 as following:

$$\Phi_b(W_D) = \frac{I_b t}{2\pi R^2 \varepsilon_0 \left[\sqrt{(W_D)^2 + R^2} - (W_D)\right]} \tag{6}$$

$$\Phi_b(W_D) = \frac{I_b t}{2\pi R^2 \varepsilon_0 \left[(W_D)\left(1 + \left(\frac{R}{(W_D)}\right)^2\right)^{1/2} - (W_D)\right]} \tag{7}$$

To simplify Eq. 7 by using the power series:

$$\left(1 + \left(\frac{R}{(W_D)}\right)^2\right)^{1/2} = 1 + \frac{1}{2}\left(\frac{R}{(W_D)}\right)^2 - \frac{1}{8}\left(\frac{R}{(W_D)}\right)^4 + \frac{1}{16}\left(\frac{R}{(W_D)}\right)^6 - \frac{15}{128}\left(\frac{R}{y(W_D)}\right)^6 + \cdots \tag{8}$$

As ($W_D$>>R), Eq. 8 can be approximated to:

$$\left(1 + \left(\frac{R}{(W_D)}\right)^2\right)^{1/2} = 1 + \frac{1}{2}\left(\frac{R}{(W_D)}\right)^2 \tag{9}$$

By compensating this approximation in Eq. 7:

$$\Phi_b(W_D) = \frac{I_b t}{2\pi R^2 \varepsilon_0}\left[(W_D)\left(1 + \frac{1}{2}\left(\frac{R}{(W_D)}\right)^2\right) - (W_D)\right]$$

$$\Phi_b(W_D) = \frac{I_b t}{2\pi R^2 \varepsilon_0}\left[\left(\frac{1}{2}\left(\frac{R^2}{W_D}\right)\right)\right] \tag{10}$$

$$\therefore \Phi_b(W_D) = \frac{I_b t}{2\pi \varepsilon_0 W_D}$$

By compensating Eq. 5, 10 and 3 the conservation energy Eq. 11 will be:

$$\frac{I_b t}{4\pi \varepsilon_0 R} - \frac{I_b t}{4\pi \varepsilon_0 W_D} = V_{sc}$$

$$\frac{I_b t}{2\pi \varepsilon_0}\left(\frac{1}{R} - \frac{2}{W_D}\right) = V_{sc} \tag{11}$$

As ($W_D$>>R) Eq. 11 becomes:

$$\frac{I_b t}{2\pi \varepsilon_0}\left(\frac{1}{R}\right) = V_{sc} \tag{12}$$

$$I_b = \frac{2\pi \varepsilon_0 R V_{sc}}{t} \tag{13}$$

Equation 13 can be used to calculate the ion beam current and eliminate the mirror phenomenon. This equation depends on three parameters which are:

- Radius of irradiation region
- Acceleration voltage used in imaging
- Imaging time (t) which is a very important factor and must be determined with high precision at work

It is noticed, from the results in Table 1 that there is an excellent compatibility between with theoretical and practical results that previously published. The error rate is reduced if the imaging time is well defined, i.e., these calculations depend on the accuracy of the imaging time.

## CONCLUSION

The obtained results showed that it is possible to calculate the ion beam current by using Eq. 13 to eliminate the mirror phenomenon. The importance of this equation comes from that it contains 3 fundamental parameters which can be determined before beginning the work, these parameters are: radius of irradiation Region ($R_s$), acceleration Voltage ($V_{sc}$) used in imaging and imaging time (t). It is noticed also that the accuracy of results depend on the accuracy of the imaging time.

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