Determination of the Trapped Charge Using Scattering Method

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Abstract: The proposed scattering model can be used to express the total charge implanted in an insulator for Polyethylene terephthalate (PET). Using experimentally determined quantities in the ion mirror image method (IMIM) inside a focused ion beam (FIB) microscope. The scattering model establishes a physical foundation for IMIM charge determination. After theoretically obtaining the trapped charge values, using MATLAB simulationand compared it with the practically trapped charge value of the polyethylene terephthalate material to check if there is a match between the both results.

***Keywords*:** Scattering Method (SM),Trapped Charge (Q_t),Ion Mirror Image Method (IMIM).

1. Introduction (12 bold)

In many technological fields the electronic and optical devices have become an analytical technology which cannot be ignored[1]. The focusing ion beams (FIB) device technique essentially evolved between the 70 and 80 Century, the first device commercially manufactured was the modern systems of focusing ion beams (FIB) device have been widely available in advanced scientific researchers [2-6]. Through this technique and when directing the ion beam from the charged gun with high voltage towards the insulating sample, this sample will acquire a charge similar to the ray that hit the surface of the sample (and the reason why this charge does not leak from the surface is that the material used is insulating i.e. non-conductive) and as a result of the trapped charge the ion path will be destroyed. Then we will irradiate with a second energy lower than the first. Thus, the ion that has less kinetic energy will be reflected in the back parts of the chamber due to the force of repulsion between the ions trapped on the surface of the material and the ions released from the gun. As for the backward reflected ions, they will collide with the inner walls of the chamber, which in turn leads to the release of secondary ions, and the detection of these ions by the detector leads to imaging the chamber from the inside , and this known as the mirror effect, i.e. the ionic mirror effect[7, 8]. In

(FIB) microscope this phenomenon has been observed by Croccolo [9], later by the researcher Muayyed Jabar Zoory[8, 10-13].

1.1 procedures and materials

In this paper we use the polyethylene terephthalate insulation material. Were invented by John Rex Whinfield and James Tennant Dickson in 1941[14], is the most widely used thermoplastic polymer resin in the polyester family, and it was employed in a variety of applications. PET is a colorless, semi-crystalline resin in its native state. PET can be semi-rigid to rigid depending on how it is produced, and it is extremely lightweight. It works effectively as a gas and moisture barrier, as well as an alcohol and solvent barrier. It is tough and resistant to damage[15]. In this work, we will focus on employing the scattering method in the focusing ion beam device in order to calculate the value of the trapped charge(Q_t) theoretically and compare it with the practical results of the trapped charge value of the PET material. In addition to finding the radius of the equipotential surface(r), the image of distinctive feature(r_v), and finally the scanning potential (V_{sc}).

2. Theoretical Analysis

Several years earlier, the mirror image method (MIM) was suggested [16]. Since then, it has been used to determine how much charge is stuck in dielectric samples and what the potential distribution is like [17, 18]. The purpose of this work is to investigate the path of an ion moving in an electrostatic field and to comprehend the physical processes involved in ion dispersion in MIM. To explain such a procedure, the classic Kepler equation for calculating the path of a satellite in space has been adjusted. In this method, amount of positive trapped charge is injected into the dielectric sample at a very high voltage, and then the sample is scanned with a beam of positive ions at a low imaging voltage. As a result of the presence of the trapped charge, the ion will deviate from its path. The ions that have a greater angle of deviation than the other will collide with the inner surface of the FIB and produce secondary ions. These ions will be collected by the detector and thus we will get a mirror image, see figure (1).

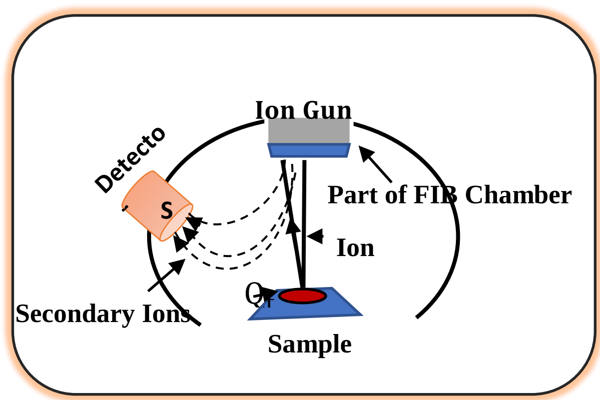

Fig. (1): A Sketch in a (FIB) chamber showing the Ion Mirror Effect (IME).

Therefore, we assume that the charge that is included in the insulating sample is a point charge Q_t, and therefore the electric potential $V_{(r)}$is given by the following equation;

$$V_{(r)} = \frac{KQ_t}{4\pi\epsilon_\circ r} \tag{1}$$

Where κ =2/ [$(\varepsilon_r + 1)$], (r) is distance from a source point charge . So to find the value of Q_t that injected in the sample we use" Kepler's law " [19].The trajectory of the ion in the above repelling potential is a hyperbola of which the equation in polar coordinate (r, θ) is given by;

$$\frac{1}{r} = \frac{g\ cos\theta - 1}{f} \tag{2}$$

Where g and f are the parameter of the ion path trajectory. And we can express them by the two equation below;

$$g = \left[1 + \left(\frac{8\ \pi\epsilon_\circ\ V_{sc}\ \mathrm{C.P}}{kQ_t}\right)^2\right]^{0.5} \tag{3}$$

$$f = \frac{8\ \pi\epsilon_\circ V_{sc}\mathrm{C.P}^2}{k\ Q_t} \tag{4}$$

Where(C. P) is known as the collision parameter, and we can calculate it from mirror image method .So the quantity of trapped charge Q_t, collision parameter C. P, and scattering angle γ are related as follows ;

$$Q_t = \frac{8\ \pi\epsilon_\circ\ V_{sc}\ C.P}{k\ cot(\gamma/2)} \tag{5}$$

From figure (2), we can find the distance between reflected-back probing ion and the optical axis of (FIB) column which called transverse distance and also the equation of working distance.

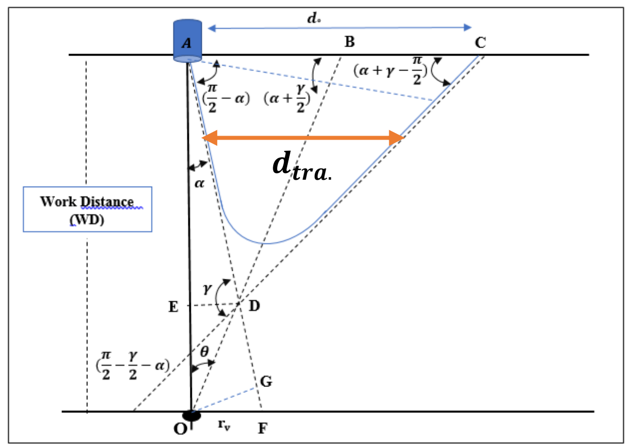

Fig. (2): A diagram of the values of the probing ion angles in trigonometry.

Using simple geometrical calculations as shown below. In Δ AOD with using of sines law [20], one can get;

Using simple geometrical calculations as shown below. In Δ AOD with using of sines law [20], one can get;

$$\frac{\overline{OD}}{sin(\alpha)} = \frac{\overline{AO}}{sin(\frac{\pi}{2} + \frac{\gamma}{2})} \tag{6}$$

Since the $\overline{AO} = WD$ (Working Distance), so;

$$\overline{OD} = WD\frac{sin(\alpha)}{cos(\frac{\gamma}{2})} \tag{7}$$

In similar way, one can get the following relation from Δ ODE;

$$\frac{\overline{ED}}{sin\left(\frac{\pi}{2} - \frac{\gamma}{2} - \alpha\right)} = \frac{\overline{OD}}{sin\left(\frac{\pi}{2}\right)} \tag{8}$$

By substitute the value of equation (7) into an equation (8), and opening the sine angle, we get the following equation;

$$\overline{ED} = WD\frac{sin(\alpha)}{cos(\frac{\gamma}{2})}\, cos\left(\frac{\gamma}{2} + \alpha\right) \qquad (9)$$

Applying the sines law in Δ AOB the following formula may obtain;

$$\frac{\overline{AB}}{sin\left(\frac{\pi}{2} - \frac{\gamma}{2} - \alpha\right)} = \frac{\overline{AO}}{sin(\frac{\gamma}{2} + \alpha)} \qquad (10)$$

$$\overline{AB} = WD\cot\left(\frac{\gamma}{2} + \alpha\right) \qquad (11)$$

Now for the triangle BCD and ABD the following expression can be formulated respectively;

$$\frac{\overline{BC}}{sin\left(\frac{\pi}{2} - \frac{\gamma}{2}\right)} = \frac{\overline{BD}}{sin\left(\alpha + \gamma - \frac{\pi}{2}\right)} \qquad (12)$$

$$\frac{\overline{AB}}{sin(\frac{\pi}{2} - \frac{\gamma}{2})} = \frac{\overline{BD}}{\sin\left(\frac{\pi}{2} - \alpha\right)} \qquad (13)$$

By substitute the equation (11) and the value of $\overline{BD}$ from equation (12) in to equation (13), so we get this formula;

$$WD\frac{cot\left(\frac{\gamma}{2} + \alpha\right)}{sin\left(\frac{\pi}{2} - \frac{\gamma}{2}\right)} = \overline{BC}\,\frac{sin\left(\alpha + \gamma - \frac{\pi}{2}\right)}{sin\left(\frac{\pi}{2} - \frac{\gamma}{2}\right)} \qquad (14)$$

$$\overline{BC} = WDcot(\frac{\gamma}{2} + \alpha)\left[\frac{-cos(\alpha)}{cos(\alpha + \gamma)}\right] \qquad (15)$$

Because we have the following formula $\overline{AC} = \overline{AB} + \overline{BC}$ $and\ (\overline{AC} = d_{tra.})$ Therefore, we can conclude from that;

$$d_{tra.} = WD\cot\left(\frac{\gamma}{2} + \alpha\right)\left[1 - \frac{cos(\alpha)}{\cos(\alpha + \gamma)}\right] \qquad (16)$$

From equation (16) we can find the angle (γ) described by ;

$$d_{\circ} - WD\cot\left(\frac{\gamma}{2} + \alpha\right)\left[1 - \frac{cos(\alpha)}{\cos(\alpha + \gamma)}\right] = 0 \qquad (17)$$

$$d_{\circ} - d_{tra.} = 0 \qquad (18)$$

The image of distinctive feature $\overline{OF} = r_v$, from Δ AOF can be formulated to be as in the following form;

$$r_v = WD\, tan(\alpha) \qquad (19)$$

Finally, the radius of the potential surface at points D can be obtained from figure 2 by geometrical consideration,

$$r = r_v\frac{cos\ \alpha}{cos(\gamma/2)} \qquad (20)$$

We will also use the approximation of Point Charge followed by the researcher Mohamed Hasan Khanjar[21] ,this approximation assumes that the distribution of the charges on the surface appears to be a point charge, so when, the point charge Q is located at the origin, the potential Φ(r) at position vector (r) becomes [22].

$$\Phi(r) = \frac{Q}{4\pi\epsilon_0 r} \qquad (21)$$

Then the potential distribution equation for the incident ion beam is written as follows [23]:

$$\Phi_b(WD - r) = \frac{Q_b}{4\pi\epsilon_0(WD - r)} \qquad (22)$$

Where (WD) is work distance, (r) is optical axis, and (Q_b) is beam surface charge.

We may compute the trapping charge potential (Φ_s) for any point on the optical axis r using the equation when a trapping charge (Q_t) is implanted inside the sample surface whose dielectric constant is (ϵ_r)[24]:

$$\Phi_s(r) = \frac{Q_t}{2\pi\varepsilon_0(1+\epsilon_r)r} \qquad (23)$$

The incoming ions will bounce at a specific point to the inner surface of the microscope chamber when the total of the beam potential (Φ_b) and the acceleration potential (V_{sc}) equals the surface potential (Φ_s). This point depends on the trapped charge, beam current, and nature of the dielectric medium.

The mentioned in the above paragraph can be expressed as the following:

$$\Phi_s = \Phi_b + V_{sc} \qquad (24)$$

3. Results and Discussion

In this section we will study the effect of incident angle and the effect of scanning voltage as follows:

First we will study the effect of incident angle, through the equation (18), and at V_{sc}=5kV we found the γ and α values were extracted, through which the equation becomes equal to zero. After that we found r, r_v values through which we obtained the charge values below. That is comparable for the practical PET values.

Table 1: Extract of α (deg.), $\gamma(deg.), r_v(m), r(m)$ and the trapped charge values $Q_t(C)$.

$\alpha\ (deg.)$	$\gamma(deg.)$	$r_v(m) * 10^{-4}$	$r(m) * 10^{-4}$	$Q_t(C) * 10^{-9}$
0.045°	161.41°	0.23562	1.4588	0.17968
0.064°	161.37°	0.33510	2.0703	0.25499
0.096°	161.30°	0.50266	3.0940	0.38108

In addition, the alpha values in the table above are the values at which the transverse distance equals the width of the column diameter (i.e. $d_\circ = d_{tra.}$). Next, we will study the effect of different angle of incidence on the various of practical trapped charge values. And calculate the amount of kinetic energy V_{sc} needed to accelerate the ions so that $(d_\circ = d_{tra.})$.

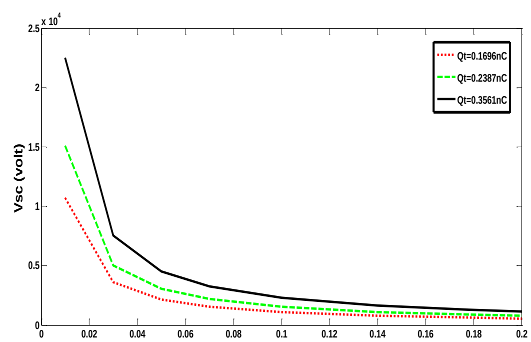

Fig. (3): various of V_{sc} for different angles of incidence at a limit values of the trapped charge.

We notice from the figure 3 that at low incident angle values we need a very high potential in order to get rid of the mirror effect. And when the value of incident angle gets increase the potential we need to get rid of the mirror is less.This conclusion prompts to study the effect of potential for different angles of incidence on the path of the descending beam. As shown in figures (4-6)

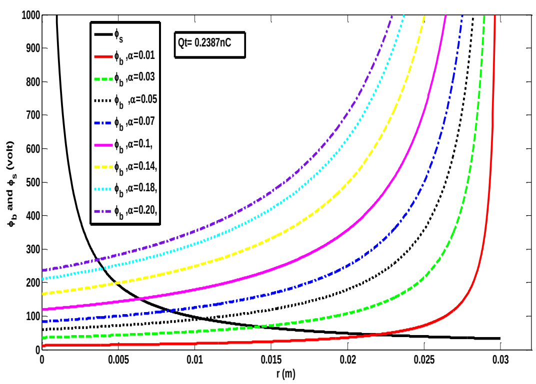

Fig. (4): The relationship between the beam potential(Φ_b)and sample potential (Φ_s) with r(m) at ($Q_t =$ 0.1696 nC)for different incident angle.

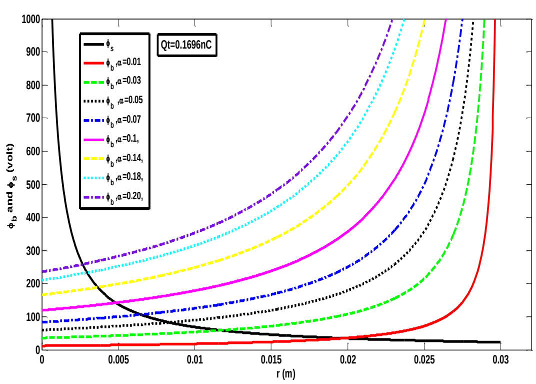

Fig. (5): The relationship between the beam potential(Φ_b)and sample potential (Φ_s) with r(m) at ($Q_t =$ 0.2387 nC) for different incident angle.

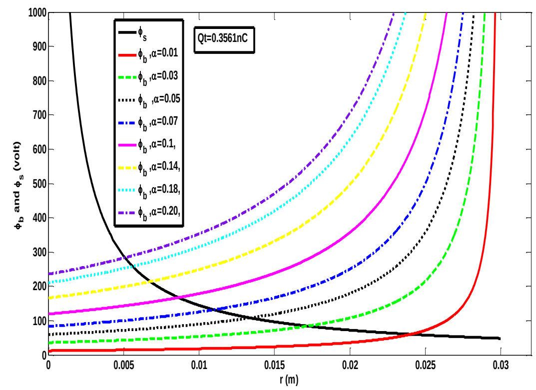

Fig. (6): The relationship between the beam potential(Φ_b)and sample potential (Φ_s) with r(m) at ($Q_t =$ 0.3561 nC) for different incident angle.

Figures (4-6) demonstrate the distributions of the beam potential(Φ_b)and sample potential (Φ_s), derived from equations (22) and (23) respectively,along the optical axis-r. The residual parameters are fixed at the following typical values: trapped charge (Q_t= 0.1696 ,0.2387,0.3561 nC), dielectric constant ϵ_r = 3.43 (respect to polyethylene terephthalate material), and work distance (W=30mm). The trapped charge changes with a different angle.

It is also obvious through the three figures above, when the angle of incidence is increased, we notice a large increase in the potential along the distance between the column and the surface of the sample, as the trapped charge remains constant. This means an increase in the charge of the fallen ions. Although V_{sc} is constant in our calculations, we noticed that the angle of incidence gives additional strength. On the resistance of the sample potential (i.e., as the incident angle increase, the greater resistance to the sample potential increase), and this means giving an opportunity for the ions to reach the sample surface by increasing the angle of incidence.

As the points of intersection that appear in the figures, these are the points at which the mirror phenomenon disappearing and the closest distance the potential reaches. This means that we provided the ions with a high momentum, and thus the kinetic energy increased, that meaning the ion got closer. This behavior is close to the behavior used by the researcher Mohamed Hasan Khanjar [21], but it changed the momentum of the ions through the beam current, and this result we have reached reinforces the researcher's findings.

Second we will study the effect of acceleration voltages of various trapped charge values

Table 2: Calculate the amount of charge from the dispersion equations according to the scanning voltages at specified angles of incidence ($\alpha\ (deg.)$ =0.01° ,0.03° , 0.05°, 0.07°, 0.1°).

$V_{SC}(kV)$	5	6	7	8	9	10
Q_1*10^{-9}C	0.0079	0.0949	0.1107	0.1265	0.1422	0.1581
Q_2*10^{-9}C	0.2368	0.2842	0.3315	0.3789	0.4263	0.4736
Q_3*10^{-9}C	0.3938	0.4726	0.5514	0.6301	0.7089	0.7876
Q_4*10^{-9}C	0.5501	0.6602	0.7702	0.8802	0.9903	1.1003
Q_5*10^{-9}C	0.7834	0.9400	1.0967	1.2534	1.4100	1.5667

Through the above table, the charge values were calculated from an equation (5) of scattering method for the different survey voltages and we noticed that the change of the scan voltage with the charge is small compared to the change of the angle of incidence with the charge, which is large. Therefore, we conclude that the angle of incidence is the parameter that affects the disappearance of the mirror, and this allows us to photograph with lower energy, and this result proves what the researcher observed [25]

4. Conclusion

We compute theoretically the trapped charge that is comparable for the practical PET values using scattering method. Also we calculate the amount of kinetic energy V_{sc} needed to accelerate the ions so that $(d_{\circ} = d_{tra.})$. When the value of incident angle gets increase the potential we need to get rid of the mirror is less. This conclusion prompts to study the effect of potential for different angles of incidence on the path of the descending beam. We found the points of intersection, these are the points at which the mirror phenomenon disappearing and the closest distance the potential reaches. We conclude that the angle of incidence is the parameter that affects the disappearance of the mirror, and this allows us to photograph with lower energy.

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