Characteristics of probing electrons behavior inside the chamber of scanning electron microscope

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Abstract. The electron mirror phenomenon has been explored to describe the behavior of a probing electron trajectory inside the chamber of scanning electron microscope (SEM). This investigation has been carried out by means of the modulated mirror plot curve technique. This method is based on expanding sample potential to a multipolar form to detect the actual distribution of the trapped charges. Actually an experimental result is used to guiding results of this work toward the accurate side. Results have shown that the influence of each type of multipolar arrangement (monopole, dipole, quadruple, octopole …etc.) mainly depends on the driving potential.

Keywords: SEM, Mirror effect, Charging process, Insulators samples, Electron beams.

1. Introduction

Now, it is well known that as long as a dielectric material is bombarded by electrons beam, some of these electron straps at surface or even within bulk material [1,2]. Such a situation leads to what so called Charging Effect (CE) [3,4] which is becoming very important to comprehend. The use of dielectric material in modern science and technology significantly depends on the realization of CE which in turn could lead to better applications [5,6].

The CE can be investigated in terms of several techniques[7], however, the one that is called Scanning Electron Mirror Method (SEMM) is followed in this work. Such an investigation technique provides an excellent ability to control and analyze CE [8]. Anyway, its principle work can be summarized by two steps. The first one imply an implantation of a trapping negative charges beneath the dielectric sample surface using a focused electron beam [9]. In the second step, the scanning mode is used to observe the sample surface with a potential ranging from fractions to a few kilovolts [10]. Actually, increasing the electric field could be strong enough to prevent the next probing electrons from reaching the sample surface. In fact, the surface acts as a convex mirror and reflects the electrons. The mirrored backward electrons will attack the chamber inner surfaces and create new Secondary Electrons (SE), so, their detection will lead to imaging of the insider chamber space rather than the sample.
Obviously, sample potential regulates the characteristics of the appeared electron image, which in turn depend on the way that the trapped charges distribute on the sample surface. So, the knowledge of trapped charges distribution profile is a crucial task to specify physiognomies of mirror images. Recently, the modulated mirror plot curve technique has been presented to detect the actual distribution of the trapped charges[11]. This method is based on expanding sample potential to a multipolar form to identify the spreading of the trapped charges. Current work aims to find the contribution weight of each multipole expansion term which may involve in building up the sample potential.

2. Material and method
The method of charge images has been used recently to solve Poisson's equation inside the chamber of a scanning electron microscope (SEM). Subsequently, the solution in the free space is given by [11];

\[ U(\vec{r}) = \frac{k}{4\pi\varepsilon_0} \int \frac{\rho(\vec{r})}{|\vec{r} - \vec{r}'|} \]  

(1)

where \((\varepsilon_0)\) is the free space permittivity, \((k)\) is equal to\([2/(\varepsilon_r + 1)]\), and \((\varepsilon_r)\) the relative permittivity. However, equation (1) represents the electrostatic potential at any point located by the position vector \((\vec{r}')\) throughout the space (SEM-chamber) that deduced due to an accumulation of a volumetric charges distribution of amount \(\rho(\vec{r}')\) located at \((\vec{r}')\). In order to grand equation (1) ability to describe charge extension within the sample, the numerator of this equation is expanded and hence the following expression is obtained;

\[ U(\vec{r}) = \frac{kQ_t}{4\pi\varepsilon_0 r} - \frac{3kQ_t r}{32\pi\varepsilon_0 r^2} + \frac{kQ_t r^3}{64\pi\varepsilon_0 r^4} - \frac{3kQ_t r^5}{512\pi\varepsilon_0 r^6} + \frac{3kQ_t r^7}{1024\pi\varepsilon_0 r^8} + \cdots \]  

(2)

where \((Q_t)\) is the trapped charge. The \(n^{th}\) term in this equation represents the \(n^{th}\) order of multipole moment of the charge distribution of \(\rho(\vec{r}')\). So, the terms of \((n = 0, 1, 2, 3, 4, 5, \text{ and } 6)\) are respectively the; monopole, dipole, quadrupole, hexapole, octopole, decapole, and dodecapole moment of the trapped charge distribution.

Mirror plot curve is represented the diagram that reveals the relation between reciprocal of Gaussian surface radius and the potential which is used to accelerates incoming electrons \((V_{sc})\). Consequently, equation (2) has been modified to imply this aspect as in the following formula;

\[ \frac{1}{r} = \frac{1}{R} \left\{ \frac{3r'}{8R^2} + \frac{r'^3}{16R^4} + \frac{3r'^5}{128R^6} + \frac{3r'^7}{256R^8} + \cdots \right\} \]  

(3)

where \(R\) is the radius of Gaussian surface for the monopole moment charge distribution which equal to \(\left(\frac{kQ_t}{4\pi\varepsilon_0 V_{sc}}\right)\). Indeed, equation (3) shows the mirror plot curve that corrected up to the seventh order, and the even power of \(n\) are vanishes due to the symmetry of problem. Thereby, it could be adopted to simulate a real (experimental) plot curve and hence verify the distribution profile of trapped charges being taken. Furthermore, contribution of each term should be examined versus the scanning potential in order to define whom the distribution look like to the incoming electrons. Anyway, this is the task of the coming next section.

3. Results and Discussion
Characteristics of a mirror image are mainly depending on the distribution profile for a sample potential that deduced by trapped electrons. Figure 1 shows the potential distribution along the radius of Gaussian sphere surface, for the first four orders of multipole moment terms in equation (2) and the equation itself. These curves are computed at fixed values of the penetration depth and trapped charges namely 10.6 \(\mu\)m and 0.064 nC respectively. Obviously, the monopole term is mainly controlling the contribution in equation (2) along the range of the radius of Gaussian sphere surface. This gives an indication that the higher order of electrons configuration are formed in the regions where a high concentration of electrons being trapped.
In order to provide present calculation a practical interest, some results that presented in the literature[12] have been used to compare with the outcome of equation (3). According to this reference, a Poly(methyl methacrylate) (PMMA) material sample of a dielectric constant 2.6 puts under irradiation by an electron beam with the aid of SEM. This beam has accelerated up to 25 kV, and the sample being under the exposition for enough time to reach the saturation. However, the trapped charges and the probing electron penetration depths are measured to be (0.064nC) and (10.6μm) respectively.

Equation (3) and each involved term have been calculated for the values of ($\varepsilon_r$, $Q_t$) and ($r'$) mentioned above. The significance of each term that contributed to builds up this formula as a function of scanning potential are plotted in figure 1. It is seen that the term contributes most to the mirror plot curve ($1/r$) is the first (zero-order or monopole) one. Indeed, this term fund ($1/r$) by most of its total worth, and so this supplement, approximately, exceeds the hundred present of its real values for ($V_{sc}$) greater than(2kV). Such a result indicates that, at ($V_{sc}$ $\leq$ 2kV) the incident electron being at a distance approximately greater than 16mm away from the sample. Thereby, trapped charges appear to be look like a point for the incident electrons, hence, the point charge approximation works well at these relatively higher distances.
Figure 2. Outcome and the amount of each term in equation (3) versus the scanning potential.

However, when the scanning potential departs from the above mentioned value, i.e. $V_{sc} \gtrsim 2kV$, the electrons start approach further to the sample. The influence of the second (two-order or quadrupole) term becomes significant and scale down the amount of monopole term. This can directly be seen from figure 1 where the curve $(1/r)$ starts leaving the linearity behavior simultaneously when the quadrupole curve just being noteworthy. Consequently, the point charge approximation fails to work well. Therefore, a trapped charge distribution is no longer appear to be a pure point for incident electrons. Instead, it becomes a mix between point and ellipse profiles.

However, when the acceleration process increases, the contribution weight of the third, fourth and fifth terms respectively become significant. Accordingly, the mirror plot curve becomes under influence of all of these terms by an amount depends on the proceeding of the term itself. Eventually, the point charge model completely failed to represent a point distribution. Hence, incident electron sees trapped charges to be something more complicated and this intricate strength increases as the electron approaches further to the sample surfaces. For accuracy realization, values of equations (3) and its own terms are recorded in Table I.

| $V_{sc}$ (kV) | 1st term $(mm^{-1})$ | 2nd term $(mm^{-1})$ | 3rd term $(mm^{-1})$ | 4th term $(mm^{-1})$ | 5th term $(mm^{-1})$ | $1/r(eq.3)$ $(mm^{-1})$ | $1/r_{experimental}$ $(mm^{-1})$ |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0          | 0               | 0               | 0               | 0               | 0               | 0               | 0               |
| 4          | 12.517          | 0.623           | 1.83E-03        | 1.21E-05        | 1.06E-07        | 11.896          | 11.90446        |
| 8          | 25.035          | 2.491           | 2.92E-02        | 7.72E-04        | 2.72E-05        | 22.572          | 22.58321        |
| 12         | 37.552          | 5.606           | 1.48E-01        | 8.79E-03        | 6.97E-04        | 40.530          | 40.26359        |
| 16         | 50.069          | 9.965           | 4.68E-01        | 4.94E-02        | 6.96E-03        | 48.011          | 47.26521        |
| 20         | 62.587          | 15.570          | 1.14E+00        | 1.89E-01        | 4.15E-02        | 48.011          | 47.26521        |
The variations of the mirror plot curve versus trapped electrons for various values of scanning potential are plotted in figure 3 at a penetration depth of 10.6 μm. It is seen that as long as the higher concentrations of trapped electron are accumulated at the sample surface, the minimum approach distance of scanning electrons being increases. Hence, a landing electron reflected backward at higher distances from the sample surface when higher irradiation potential is used.

**Figure 3.** The behavior of mirror plot curve as a function of trapped electron amounts for different values of the scanning potential.

Figure 4 reveals the behavior of the mirror plot curve versus the penetration depth at several scanning potential values, and at the value of trapped electrons equals to 0.064 nC. Indeed, the trapped electrons implanted near the surface of the sample, and these electrons arranged themselves as a point. However, such an arrangement of accumulation takes complicated forms as long as trapped electrons deeply spread inside the sample’s body.

**Figure 4.** The behavior of mirror plot curve as a function of the penetration depth for different values of the scanning potential.
4. Conclusion
According to the results appeared in the last section, one may realize that the trapped electrons have a complicated formation at the sample’s surface. In addition, this sophistication was mutable and not stable along the travel interval of the incident electron. The results of this work have proven that multipolar expansion has an excellent ability to simulate the correspondence experimental mirror plot curves. So, this expansion may regard to be a powerful tool for detecting trapped charges distribution at dielectric materials.

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