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Positive bias and vacuum chamber wall effect on total electron yield measurement: A re-consideration of the sample current method

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The measurement of the total secondary electron yield (TEY, δ) is of fundamental importance in areas such as accelerator, spacecraft, detector, and plasma system. Most of the running TEY facilities in the world are based on the kind of bias strategy. The applied bias can assist in the collection of the secondary/primary electrons. In the prevailing sample current method, the TEY is obtained by the measurement of the current from the sample to ground with a negative/positive bias applied to the sample. One of the basic assumptions in this method is that the positive bias can retain most of the electrons emitted by the sample. This assumption is generally recognized based on the seeming fact that the low energy secondary electrons dominate the emitted electrons. In this work, by considering the full electron energy spectrum including both the true secondary and backscattered electrons, we give a new insight in this TEY measurement method. Through the analytical derivation as well as the Particle-in-Cell numerical simulation, we show that it is due to the following two factors, other than the assumption mentioned above, which make the sample current method works satisfactorily: (a) the TEY relative error is related to the TEY itself in the form of $|1-\delta|/\delta$, which indicates a smallest error when measuring samples with TEY closest to 1; and (b) the compensation effect of the vacuum chamber wall. Analytical results agree well with numerical simulations and furthermore, we present a correction method for reducing the TEY relative error when measuring samples with TEY below 1. By sweeping the positive bias from 50 to 500 V, a flat silver sample in the as-received state with maximum TEY larger than 2 and a laser etched sample with maximum TEY close to 1 were measured for further verification. The obtained experimental results agree well with the theoretical analysis. *Published by AIP Publishing.*
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I. INTRODUCTION

Secondary electron emission from the electron-solid interaction has been thoroughly studied for its wide applications in areas such as accelerators,[1,2] vacuum electronic devices,[3] microscopic analysis,[4] and spacecrafts.[5] One of the most important parameters for this phenomenon is the total secondary electron yield (TEY), which describes the ratio between the number of emitted electrons and that of incident electrons. Based on the generation process, secondary electrons can be classified into three categories: backscattered electrons, rediffused electrons, and true secondary electrons.[6] Each kind of these electrons has its own yield, energy, and direction distribution.

Compared with other aspects of secondary electron research, e.g., the modifications of material's TEY and their applications,[2,7] research works on the measurement of the TEY advances slowly. Until today, most of the running facilities for the measurement of the TEY worldwide[6,8,9] do not have much difference in principle with the ones developed more than 30 years ago.[10,11] In all of these methods, some types of bias strategies are thoroughly adopted for the purpose of: (a) collecting primary electrons with usually a positive bias on the Faraday cup[12] or the sample;[13] (b) collecting secondary electrons with usually also a positive bias on the grid shell;[6,9] and (c) collecting secondary electron information indirectly with a minus bias on the sample.[13] It can also be noted from the literatures that, with regard to the bias voltage, it varies from one set-up to another even for a same purpose. For example, in order to measure primary electrons by a Faraday cup, the bias in Ref. 12 is 36 V, while in Ref. 14 it is 123 V. This is also the case for the sample current method. For example, to measure the primary current, in Ref. 1, the bias applied to the sample is 150 V, while in Ref. 13 it is 500 V. In fact, this variance of bias originates from factors relating to the structure and material of the vacuum chamber (e.g., the shape of the chamber, the diagnostics tools embed in the chamber). All of these details may have some effects on the field distribution inside the chamber, which results in different electron dynamics. However, how these facility effects influence the TEY measurement is treated only by very few works. In Ref. 12, the facility effect was considered through the Particle-in-Cell (PIC) simulation with a focus on the

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[a)] Authors to whom correspondence should be addressed. Electronic addresses: yongning@mail.xjtu.edu.cn and cuiwanzhao@126.com electric field influence on electron trajectory. The backscattered electrons are omitted in their simulation. Compared with the DEESSE system,[12] the TEY system in Ref. 13 adopted the sample current method. With regard to the measurement of the primary electron current, the sample current method seems to be more convenient than the Faraday cup method since, for the latter method, the precise location of the cup is required to ensure that all the primary electrons are absorbed by the cup for the sample current method. However, there is a basic assumption for the sample current method: when measuring the primary electrons by the positive bias applied on the sample, all the emitted electrons are retained by the sample. In a usual case, this assumption is believed to be correct since most of the secondary electrons are of energies lower than the applied bias.

In this work, we present a rigorous quantitative analysis on the validity of the assumption of the sample current method. First of all, we develop an analytical model for the TEY measurement error induced by the positive bias taking into account the backscattered and rediffused electrons. Then, we use the PIC simulations, which also take the backscattered and rediffused electrons into account, to verify the developed analytical model, and we also present a correction method for reducing the TEY measurement error of samples with TEY below 1. Finally, we present the TEY measurement results of both an as-received flat sample and a laser etched porous sample with a bias sweeping from 50 to 500 V for further verification.

II. ANALYTICAL MODEL AND RESULTS

In the sample current method,[13] the TEY is measured by a two-step approach at primary energy E_p: first, apply a positive bias V_b to the sample and measure the current from the sample to ground I_{p,E_p,V_b}; second, apply a negative bias to the sample and also measure the current from the sample to ground I_{R,E_p}. Then, the TEY δ_{E_p} at the primary electron energy E_p should be

$$\delta_{E_p} = (I_{p,E_p,V_b} - I_{R,E_p})/I_{p,E_p,V_b} = 1 - I_{R,E_p}/I_{p,E_p,V_b}. \tag{1}$$

For this two-step approach, it is assumed that, when the sample is positively biased, all the emitted electrons from the sample can be retained by the sample. Usually, the positive bias was no more than hundreds of volts. For example, this bias was set at 500 V.[13] In fact, no matter what the positive bias is, the impact energy is always equal to the primary energy plus the bias voltage. Thus, part of the emitted electrons (namely, part of the rediffused electrons and all of the backscattered electrons) will have energies larger than the bias and they will escape from the sample. Thus, the measured primary electron current will be smaller than the real value. In a usual case, it is just qualitatively estimated that the escaped electrons only take a rather small part of all the emitted electrons.[15–17] So, the current I_{p,E_p,V_b} can be regarded as the real primary electron current without introducing much error in the TEY measurement. Next, we will show that this problem should be interpreted in a different way.

According to the theory of propagation of the error, the absolute error of TEY should be (neglecting the measurement error of I_{R,E_p})

$$\Delta\delta_{E_p} = \left|\frac{\partial}{\partial I_{p,E_p,V_b}}\delta_{E_p}\right|\Delta I_{p,E_p,V_b} = |1-\delta_{E_p}|\frac{\Delta I_{p,E_p,V_b}}{|I_{p,E_p,V_b}|}. \tag{2}$$

Similarly, the relative error of TEY induced by the error of the primary electron current should be

$$\frac{\Delta\delta_{E_p}}{\delta_{E_p}} = \left|\frac{\partial}{\partial I_{p,E_p,V_b}}\ln\delta_{E_p}\right|\Delta I_{p,E_p,V_b} = \left|\frac{1-\delta_{E_p}}{\delta_{E_p}}\right|\frac{\Delta I_{p,E_p,V_b}}{|I_{p,E_p,V_b}|}. \tag{3}$$

Thus, it can be seen that the absolute error of TEY $\Delta\delta_{E_p}$ is proportional to the relative primary current error $\Delta I_{p,E_p,V_b}/|I_{p,E_p,V_b}|$ and, what is more, the proportionality coefficient ($|1-\delta_{E_p}|$) is related to the TEY δ_{E_p} itself. The most important implication of Eqs. (2) and (3) is that the validity of the sample current method for the TEY measurement does not only rely on the measurement accuracy of I_{p,E_p,V_b}. For example, if the relative error $\Delta I_{p,E_p,V_b}/|I_{p,E_p,V_b}|$ is 10%, then the TEY error could be varied in a wide range: for typical metals, such as silver, the maximum TEY is about 2 which indicates that the absolute error of TEY would be also about 10% according to Eq. (2), while the relative error would be about 5% according to Eq. (3); but for insulators, the maximum TEY may be as high as 5; thus, the absolute TEY error would be about 40% (Eq. (2)), while the relative error would be about 8%. Particularly, when the TEY is close to 1, the absolute/relative error of TEY will be close to zero. This is because, in this case, the current I_{R,E_p} will be zero as the incident number of electrons is equal to the emitted electrons and finally results in the accurate TEY (see Eq. (1)). So, with regard to the measurement of the crossover energy points E_1 and E_2, which are two of the most critical parameters in the multipactor analysis,[18] the sample current method is a quite acceptable method. Besides, since the TEY is related to primary energy, it can be expected from Eqs. (2) and (3) that the TEY error will also dependent on the primary energy. Until now, only the first part of the right side of Eq. (3) is considered. Next, we will show how to evaluate the second part ($\Delta I_{p,E_p,V_b}/|I_{p,E_p,V_b}|$).

It seems that the relative error of the primary current ($\Delta I_{p,E_p,V_b}/|I_{p,E_p,V_b}|$) is due to the inability of the positive bias to pull back all the emitted electrons. This loss of electrons can be calculated using the secondary electron energy spectrum. Suppose the energy spectrum of the secondary electron is $S_{E_{impact}}(E_{se})$, then we have

$$\frac{\Delta I_{p,E_p,V_b}}{|I_{p,E_p,V_b}|} = \int_{E_{se}=V_b}^{E_{se}=V_b+E_p} S_{V_b+E_p}(E_{se})dE_{se}. \tag{4}$$

Here, E_{se} is the energy of secondary electrons. In Ref. 6, a similar model is presented for the evaluation of the effect of the positive sample bias on the measured primary electron current. The difference between these two models lies in the model of the secondary electron energy spectrum: our model of the energy spectrum includes the backscattered electrons; Ref. 6 excludes the backscattered electron in their energy spectrum but introduces the backscattered electron yield separately. Therefore, the physical meanings of these two models are in fact equivalent. Now, we have the full analytical model of the TEY relative error by combining Eqs. (3) and (4)

$$\frac{\Delta\delta_{E_p}}{\delta_{E_p}} = \frac{|1-\delta_{E_p}|}{|\delta_{E_p}|}\int_{E_{se}=V_b}^{E_{se}=V_b+E_p} S_{V_b+E_p}(E_{se})dE_{se}. \quad (5)$$

The first term on the right hand side of Eq. (5) ($|1-\delta_{E_p}|/|\delta_{E_p}|$) indicates that the TEY error will increase remarkably when the TEY is close to 0. In other words, when the sample under test is of TEY rather lower than 1 or the primary electron energy makes the corresponding TEY approaches 0, the TEY error may be unacceptable. However, in fact, the lost electrons (part of the rediffused electrons and all of the backscattered electrons) will hit the vacuum chamber wall and excite tertiary electrons. These tertiary electrons will go back to the sample due to the positive bias applied to the sample and thus compensate the loss to some degree. For the tertiary electrons, the escaped secondary electrons emitted from the sample act as the primary electrons. So, for these tertiary electrons, their primary energy ranges from 0 to E_p (note that the positive bias V_b acts as a retarding potential). We divide this energy range into N parts and suppose that, in each part, the TEY of the vacuum chamber wall is constant (denoted as $\delta_{(n-1)\Delta E}$ with $\Delta E = E_p/N$). To facilitate the analysis, we define an effective TEY (denoted as $\delta_{E_p,wall,eff}$) for the chamber wall in the energy range and thus we have

$$\delta_{E_p,wall,eff} = \sum_{n=1}^{N=E_p/\Delta E} \delta_{(n-1)\Delta E}\int_{E_{se}=(n-1)\Delta E}^{E_{se}=n\Delta E} S_{E_p,wall}(E_{se})dE_{se}. \quad (6)$$

Here, $S_{E_p,wall}(E_{se})$ is the secondary electron energy spectrum of the vacuum chamber wall. This effective TEY $\delta_{E_p,wall,eff}$ is related to the following factors: the primary electron energy conducting TEY measurement, the energy spectrum of the sample under test, and the TEY of the chamber wall. It is not related to the positive bias. It should be noted that these tertiary electrons go back to the sample, which can again excite electrons. We would like to evaluate these complicated cases only in later numerical simulations. For the simplified case here, the compensation effect contributes to the TEY error as follows (these tertiary electrons will affect Eq. (4)):

$$\frac{\Delta\delta_{E_p}}{\delta_{E_p}} = \frac{|1-\delta_{E_p}|}{|\delta_{E_p}|}\left(1-\delta_{E_p,wall,eff}\right)\int_{E_{se}=V_b}^{E_{se}=V_b+E_p} S_{V_b+E_p}(E_{se})dE_{se}. \quad (7)$$

It can be seen from Eq. (7) that if $\delta_{E_p,wall,eff}$ is close to 1, then the compensation effect of the vacuum chamber wall makes the TEY error close to zero. As indicated in Eq. (7), we can see that the relative TEY error depends on: (a) TEY of the sample under test; (b) secondary electron energy spectrum of the sample under test; (c) TEY property of the chamber wall; (d) the bias applied to the sample; and (e) the primary electron energy. Thus, we can see that the relative error of TEY is rather complicated than usually considered, namely, due to the escape of electrons from the sample. It should be noted that the electrons from the chamber wall may be absorbed by other accessories in the chamber; what is more, after these tertiary electrons hit the sample, they may again excite secondary electrons that may also escape. So, a more accurate evaluation, namely, numerical simulation, should take this repetitive electron emitting and impaction process into account. However, before we present numerical simulations, we would like to show some results from the analytical model. To demonstrate the relative error of TEY more clearly, we rewrite Eq. (7) as follows:

$$\frac{\delta_{E_p,meas}-\delta_{E_p,real}}{\delta_{E_p,real}} = \frac{\delta_{E_p,real}-1}{\delta_{E_p,real}}\left(1-\delta_{E_p,wall,eff}\right) \times \int_{E_{se}=V_b}^{E_{se}=V_b+E_p} S_{V_b+E_p}(E_{se})dE_{se}. \quad (8)$$

Here, $\delta_{E_p,meas}$ and $\delta_{E_p,real}$ are the measured and real TEYs, respectively. It can be seen from Eq. (8) that, when neglecting the chamber wall's effect, the measured TEY will be larger/smaller than the real TEY if the real TEY is larger/smaller than 1. However, when the chamber wall's effect is taken into account, this tendency changes when the effective TEY of the chamber wall exceeds 1. For example, if both $\delta_{E_p,wall,eff}$ and $\delta_{E_p,real}$ are larger than 1, Eq. (8) indicates that the measured TEY will be smaller than the real TEY. This could be regarded as an overcompensated case since the number of tertiary electrons is larger than the lost electrons. Similarly, the case in which $\delta_{E_p,wall,eff}$ is smaller than 1 could be regarded as an undercompensated case.

All the calculations in this work are based on the secondary electron phenomenological model of Furman.[19] We use the default values presented in CST (Computer Simulation Technology) software for both the sample and chamber wall's secondary electron emission properties (namely, stainless steel with secondary electron emission parameters from Ref. 19 was used for demonstration). To demonstrate how TEY error is affected by the factors in Eq. (7), we calculate the TEY error in three successive steps: first, we calculate the escape ratio of the so called first generation electrons (excited by primary electrons from the electron gun impinging on the sample) to show how it deviates from the common consideration in literatures; second, we take the TEY effect into consideration to show that the TEY error can be reduced due to TEY itself; last, we take the chamber wall effect into consideration to show how the compensation effect reduces the TEY error further.

The escape ratio is calculated using Eq. (4). The TEY error considering the TEY effect was obtained by Eq. (5) with the absolute operation removed (see equation in Fig. 1(b)). To consider the compensation effect, we calculate the $\delta_{E_p,eff}$ using Eq. (6) and the error using Eq. (7) with the absolute operation also removed (see equation in Fig. 1(c)). All the calculations are conducted for biases ranging from 200 to 1000 V. The results are shown in Fig. 1. With regard to the escape ratio, it is obviously higher than usually declared in the

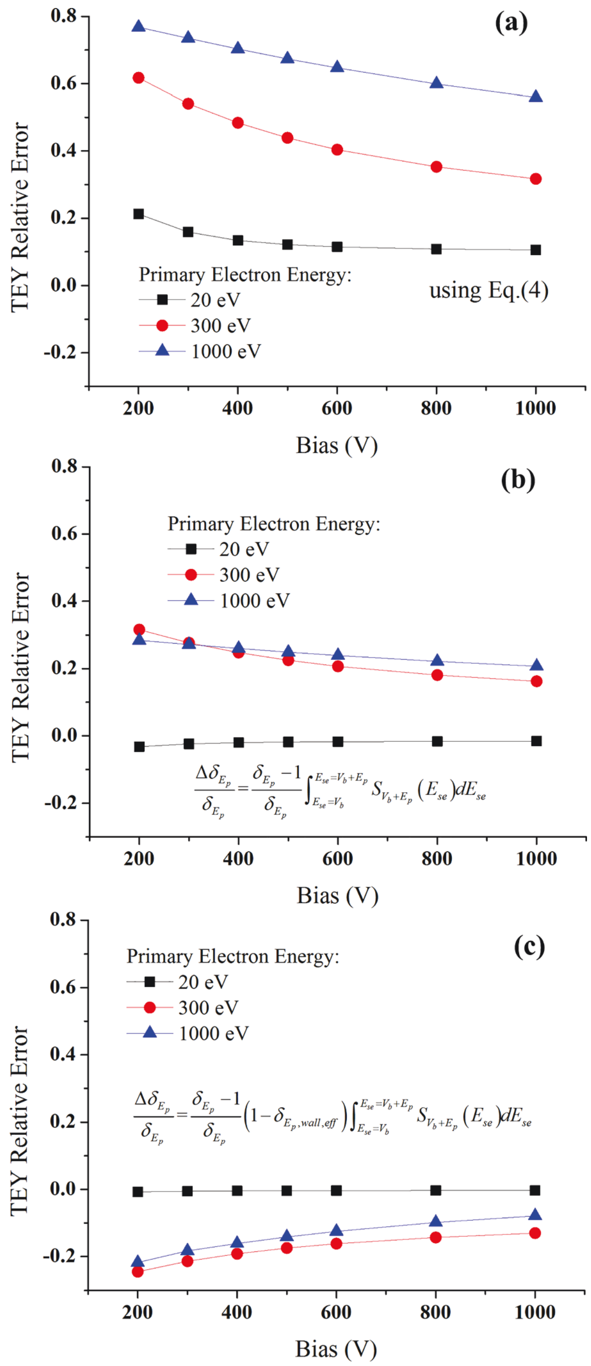

FIG. 1. Analytical prediction of the relative TEY measurement error dependence on the positive bias applied to sample: (a) consider only the escape ratio; (b) considering the TEY effect; (c) considering both the TEY effect and the compensation effect of the vacuum chamber wall. The material used for the calculation is a stainless steel from Ref. 19. The maximum TEY is ~2.1 and it occurs at the primary energy of ~300 eV.

literature.[17] The escape ratio is small only when the primary energy is small enough. For example, when the primary energy is 20 eV, the escape ratio decreases from about 20% to 10% when the bias increases from 200 to 1000 V. However, when the primary energy is 1000 eV, the escape ratio can be as high as about 80% for a bias of 200 V. It should be noted that this rather high escape ratio is originating from the secondary electron emission properties of the stainless steel[19] of which the rediffused electron yield is as high as ~0.7. So, if there are no other factors to balance this factor in the TEY measurement, then the TEY error will be unacceptable. Fortunately, the physical feasibility of the sample current method for the TEY measurement does not only rely on the small escape ratio but it also depends obviously on the TEY itself. As shown in Fig. 1(b), after considering the TEY effect, the TEY relative error is reduced considerably. For example, when bias is 500 V, the maximum error is about 25% occurring at the primary electron energy of 1000 eV. After the compensation effect was considered, the TEY error reduced further to no more than 20% for bias larger than 500 V. In total, the analytical model gives a new explanation on the feasibility of the TEY measurement by the sample current method. Fig. 1 also shows that the relative error decreases monotonously with bias. This is because the higher the bias, the smaller the escape ratio.

III. NUMERICAL SIMULATIONS AND RESULTS

To remove the assumptions adopted in the analytical model above and to further verify its results, we conducted numerical simulations based on the Particle-in-Cell (PIC) method.[12] The numerical model is schematically shown in Fig. 2 (not in scale). It uses an idea sphere representing the vacuum chamber. The size of the electron source is rather small compared with the chamber. The sample is placed in the center of the sphere. A predefined bias is applied on the sample, while the chamber wall and the electron source are grounded. The energy of primary electrons emitted from the electron source can be varied as an independent parameter. The secondary electron emission properties of both the chamber wall and the sample are defined independently. The secondary electron emission model is the same with the analytical model in Sec. II, which also takes the backscattered and rediffused electrons into consideration.

The main procedures of the simulation are as follows: first, calculate the electric field distribution in the chamber under the applied bias; second, track the primary electrons emitted from the electron gun as well as the excited

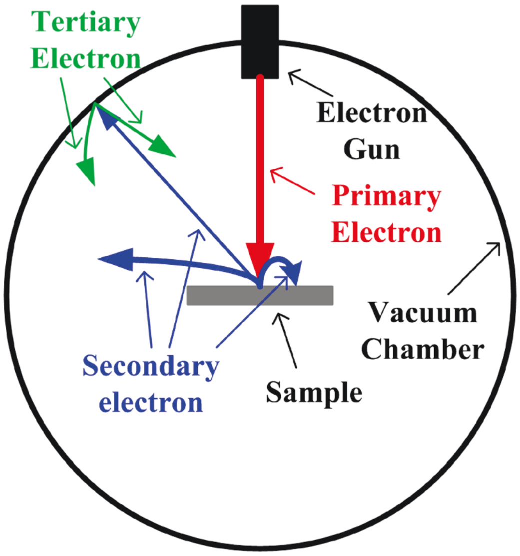

FIG. 2. Numerical model for PIC simulation: vacuum chamber is modeled as a sphere with the sample under test placed at the centered of the sphere.

secondary electrons in the later impact process (this tracking process will be terminated when the number of electrons in the chamber reduces to zero or becomes small enough); third, count the number of electrons absorbed by the sample (it is equal to the total number of impinged electrons onto the sample minus the total number of emitted electrons from the sample) at a predefined positive bias; last, calculate the numerically measured TEY using Eq. (1).

The simulated effect of the positive bias on the TEY error is shown in Fig. 3. We chose three primary electron energies for comparison: 20, 300, and 1000 eV. In these simulations, both the sample and the chamber wall have the same secondary electron emission properties with a stainless steel.[19] It can be seen that, when the primary energy is lower (e.g., 20 eV), the TEY error is smaller compared with higher primary energies (e.g., 300 eV). What is more, when the primary electron energy is higher (e.g., 300 eV), the numerical simulations predict that the measured TEY is a little smaller than the real TEY. These tendencies all agree well with the analytical model results shown in Fig. 1. However, differences between numerical simulations and analytical calculations are also observed. It can be seen from Fig. 3 that the dependence of the measured TEY on the positive bias does not obvious as in Fig. 1(c). This may be caused by the following fact: in the analytical model, it is assumed that the tertiary electrons from the chamber wall are absorbed by the sample and the secondary electrons excited when tertiary electrons impact with the sample are neglected; however, these secondary electrons generated from the tertiary electrons are taken into account in the numerical simulations. In other words, the effective TEY of the chamber wall is different between analytical model and numerical simulation.

The dependence of the measured TEY on the compensation effect and the TEY effect is shown in Fig. 4. We used two samples for demonstration: one is a stainless steel denoted as $\delta_{\mathrm{m,sample}} = 2.1$ and the other is an artificially defined sample (with maximum TEY about 1.3) denoted as $\delta_{\mathrm{m,sample}} = 1.3$. Similarly, we used three chamber wall materials denoted as $\delta_{\mathrm{m,wall}} = 2.1$, $\delta_{\mathrm{m,wall}} = 1.3$, and $\delta_{\mathrm{m,wall}} = 0.4$, respectively. Their maximum TEY is about 2.1, 1.3, and 0.4, respectively. For each combination of sample and chamber, we simulated the measured TEY with a positive bias of 500 V and the primary electron energy from 20 to 1000 eV. It can be seen that the TEY error of the sample denoted as $\delta_{\mathrm{m,sample}} = 1.3$ is obviously smaller than the sample denoted as $\delta_{\mathrm{m,sample}} = 2.1$. In fact, due to the term $|1 - \delta_{E_p}|/|\delta_{E_p}|$, Eq. (7) indicates that the TEY error tends to be small when the TEY of the sample under test is close to 1. Results in Fig. 4 also show that the measured TEY is smaller than the real TEY when the chamber wall is of higher TEY and the TEY error is smallest when the chamber wall has a TEY closest to 1. When the TEY of the chamber wall increases, the number of the tertiary electrons emitted from the chamber wall which will be absorbed by the sample also increases. This is equivalent to the increasing of the primary electron current, which results in the decrease of the measured TEY as indicated by Eq. (1). In addition, due to the term $(1 - \delta_{E_p,wall,eff})$ in Eq. (7), it can be expected that the TEY error will be smaller when the effective TEY of the chamber wall is closer to 1. So, the analytical model of Eq. (7) agrees well with numerical simulation results in Fig. 4. The other important implication of the results shown in Fig. 4 is that, for a given vacuum chamber material, the TEY error changes with the sample under test. So, this scarcely specified effect should be taken into account when measuring samples with TEY obviously different from the samples used for the calibration of a TEY set-up. In other words, it would be better to calibrate the TEY measurement set-up using samples with a wide range of TEY.

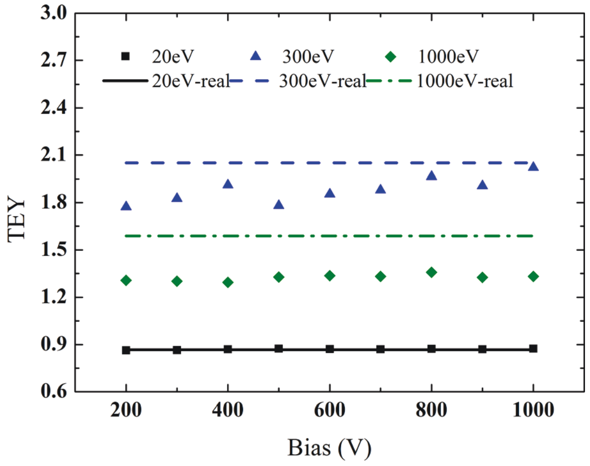

FIG. 3. Numerical simulation results: dependence of TEY on the positive bias applied on the sample. The solid line indicates the real value of TEY (the TEY of stainless steel presented in Ref. 19), while the dot indicates the simulated TEY.

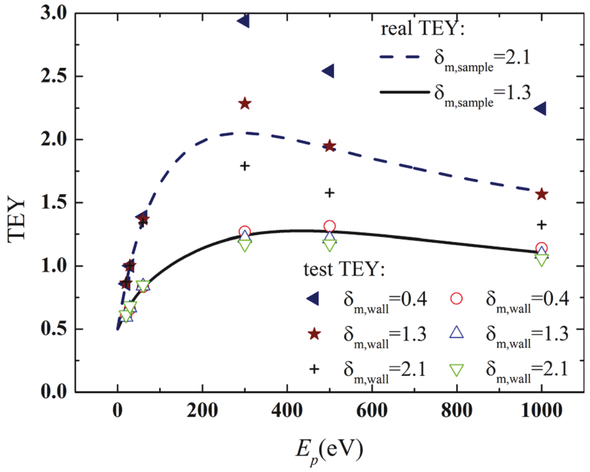

FIG. 4. Numerical simulation results: the compensation effect on numerically measured TEY. The solid/dashed line indicates real TEY: $\delta_{\mathrm{m,sample}} = 2.1$ indicates the TEY of stainless steel from Ref. 19 and $\delta_{\mathrm{m,sample}} = 1.3$ indicates the TEY of an artificially defined sample by setting the value of $\hat{\delta}_{ts}$ as 0.8, $P_{1,r}(\infty)$ as 0.4, and $\hat{E}_{ts}$ as 450 eV. The symbols indicate the numerically measured TEY of three artificially defined vacuum chamber wall materials: $\delta_{\mathrm{m,wall}} = 2.1$ indicates a stainless steel, $\delta_{\mathrm{m,wall}} = 1.3$ indicates TEY the same with $\delta_{\mathrm{m,sample}} = 1.3$, $\delta_{\mathrm{m,wall}} = 0.4$ indicates TEY with parameters: $\hat{\delta}_{ts} = 0.2$, $P_{1,r}(\infty) = 0.1$, and $\hat{E}_{ts} = 550$ eV. The primary energies of the symbols are 20, 29, 60, 300, 500, and 1000 eV.

In a usual case, TEY measurement systems are calibrated with a clean smooth surface that has a widely accepted TEY value, e.g., the gold sample. However, based on the analysis presented above, the TEY measurement error

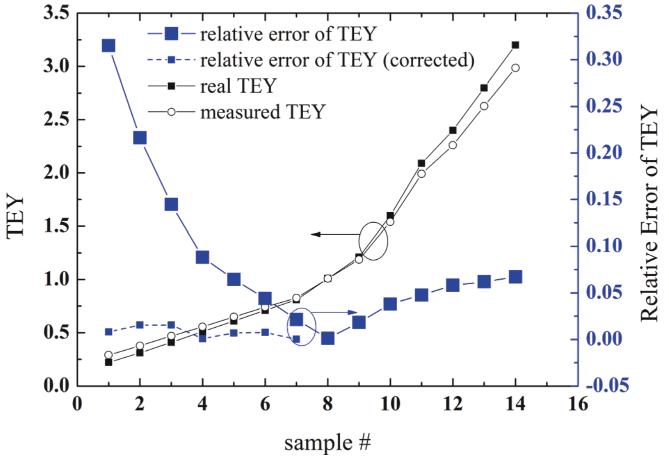

FIG. 5. The dependence of the relative error on the TEY of the sample under test. The real value of TEY, the measured TEY, the un-corrected TEY error, and the corrected TEY error are shown for comparison. The real values of TEY are obtained by sweeping the true secondary electron parameter $\hat{\delta}_{ts}$ of Ref. 19 from 0.01 to 3 with other parameters the same with copper.

is in fact related to the TEY itself (see Eq. (7)). So, when the measured sample has a very different TEY with the calibrated sample, the measurement error may be unacceptable. To study on this problem, we simulated the dependence of the TEY measurement error on the TEY itself. In our simulation, the vacuum chamber is of diameter 0.5 m and its material is stainless steel (with TEY property the same with Ref. 19). The positive bias is 500 V as in Ref. 13 (this bias setting has been verified by the calibration of the measurement system). The sample is located at the center of vacuum chamber and is of diameter 40 mm and thickness 2 mm. To obtain samples with TEY ranging from about 0.2 to 3.2 (thus, most of the metal materials and artificially low TEY surfaces are covered), we swept the parameter $\hat{\delta}_{ts}$ from 0.01 to 3 with other parameters the same with the copper in Ref. 19. The primary electron energy was 300 eV. Fig. 5 shows the results: we totally simulated 14 samples with different TEYs, and the x, left y, and right y axes show the sample's number, the TEY, and the relative error of TEY, respectively. It can be seen that the relative error reaches its minimum when the TEY is closest to 1 and reaches its maximum ~0.3 when the TEY is smallest, i.e., ~0.2. This agrees well with Eq. (7). It can also be noted that, when TEY is higher than 1, the measured values are lower than the real values and vice versa. All of these observations agree well with our analysis above. The most important point is that, when TEY of the sample under test is smaller than about 0.5, the relative error can be larger than about 10%. However, when TEY of the sample under test is larger than 1, the relative error can be totally below 7%. Thus, correction is needed when measuring samples with rather low TEY. Based on the simulation results shown in Fig. 5, we found that the following linear correction formula can be used to improve the measurement accuracy when measuring samples with TEY lower than 1

$$\delta_{true} = 1.1\delta_{test} - 0.1. \tag{9}$$

Here, δ_{test} is the measured TEY and δ_{true} is the estimated real TEY. In Fig. 5, we also show the relative error after correction using Eq. (9). It can be seen that the relative error is obviously reduced after this correction.

IV. EXPERIMENTAL RESULT AND DISCUSSION

To further verify the theoretical results presented above, two sets of TEY measurements were conducted. With regard to the measurement samples, we measured a flat silver sample in one set and a kind of low TEY sample in another set. The low TEY sample was fabricated by a laser etching process, which results in a roughened porous sample with a maximum TEY of about 1. The TEY measurement system is the same with the one used in Ref. 13. To observe the effect of the positive bias on the TEY measurement, we swept the bias applied on the sample from +50 to +500 V. The maximum positive bias available to our measurement system is +500 V which is also used as a standard positive bias. Results are shown in Fig. 6. For each sample, we present both the measured TEY and the normalized TEY, which is relative to +500 V bias at primary electron energies 40, 300, and 1000 eV. In fact, when taking the measured TEY at +500 V bias as a true value of TEY, the normalized TEY indicates the measurement error. It can be seen from the results of the flat sample shown in Fig. 6(a) that, when TEY is relatively high compared with 1 (e.g., when primary energy is 300 and 1000 eV), the measurement error is relatively large. As the positive bias decreasing from the standard +500 V to about +50 V, the measurement error can be as high as about 20%. However, when TEY is close to 1 (e.g., when primary energy is 40 eV), the measurement errors are small and almost independent of positive bias. These observed experimental results agree well with the results of analytical model and numerical simulation. The measurement results of the roughened sample shown in Fig. 6(b) indicate that, when measuring samples with TEY close to 1,

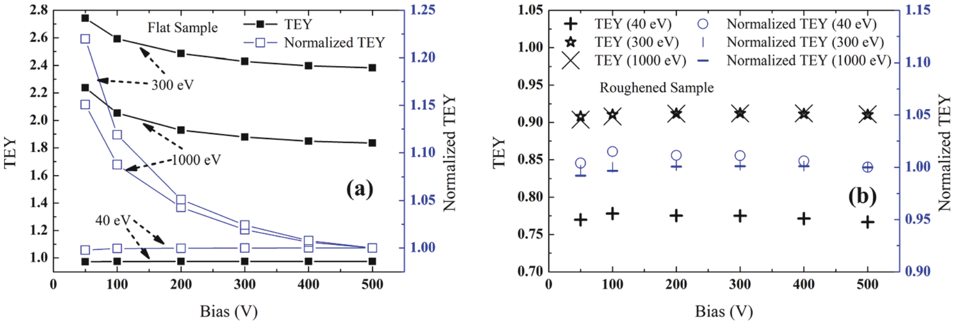

FIG. 6. Experimental results of the effect of the positive bias on the TEY measurement: (a) a flat silver sample and (b) a roughened sample with low TEY.

the effect of the positive bias is obviously weakened. What is more, this tendency is almost independent of the primary electron energy. It should be noted that, as shown in Fig. 3, when the primary electron energy is 300 or 1000 eV, the measured TEY is smaller than the real value which seems to be contradicted with the results shown in Fig. 6(a). In fact, a stainless steel with the maximum TEY about 2.1 is adopted in Fig. 3, and from the results shown in Fig. 4, we can expect that, once the TEY of the chamber wall is reduced, the measured TEY will be closer or even higher than the real TEY. Since the vacuum chamber wall has been situated in an ultra-high vacuum environment and may also be conditioned by tertiary electrons for a long time, it is reasonable to expect that the maximum TEY of the vacuum chamber wall is smaller than 2.1. In addition, accessories and the observation window of the vacuum system may also redirect electrons and thus contribute to the difference between theoretical analysis and experiment.

V. CONCLUSIONS

In this work, we present a new quantitative analysis of the TEY measurement error in the sample current method due to the positive bias. By the error propagation theory, we established an analytical model for the TEY error, which takes the sample, chamber wall, and bias into consideration. Numerical simulations based on the PIC method were also conducted, which agree well with the analytical derivations. Results show that the TEY error depends on both the sample's and chamber wall's secondary electron emission properties as well as the applied positive bias. The most important finding is that the TEY measurement system calibrated with only ideal flat surfaces is not enough for accurate TEY measurement of samples with a wide range of TEY. To overcome this normally ignored inaccuracy, we developed a correction method which should be of help to TEY researchers and engineers. Theoretical results are finally verified by TEY measurement results of both as-received flat silver sample and artificially roughened sample with a maximum TEY close to 1.

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