Secondary electron emission yield measurements of dielectrics based on a novel collector-only method

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ABSTRACT

The total electron-induced Secondary Electron Yield (SEY) of alkali-free glass has been determined by a novel technique which is solely based on the use of a collector electrode and of two interchangeable dielectric samples. The current from a charge-saturated sample provides a direct measure of the primary beam current. The SEY from the (uncharged) sample under investigation can then be determined simply as the ratio between the collector currents measured at the same electron energy from both samples. We further apply a low-current, short-pulse procedure to limit sample charging, needed to mitigate distortion of the SEY by charging effects. The potential build-up during the experiment could be reconstructed based on the primary electron currents and the measured SEY. This strategy permitted us to measure a 6-point SEY curve, without the need for intermediate discharging of the sample, as the total induced surface potential rise could be kept below +2.55 V.

1. Introduction

Dielectric materials exposed to electrons may charge up both positively and negatively at various depths, as charge is added or extracted locally. The amount of charging, its net polarity and volume distribution are governed by electron-induced Secondary Electron Emission (SEE) which is highly material dependent. This gives rise to (unwanted) local electric fields that may complicate the application of experimental techniques like Secondary Electron Microscopy (SEM) [1], Auger Electron Spectroscopy (AES) [2] and other surface sensitive diagnostics. Also, in technological fields like high-voltage and space engineering, SEE often greatly limits the performance due to local charging effects [3].

In order to predict and control the charging behavior of dielectric surfaces exposed to electrons, it is highly desirable to establish a so-called Secondary Electron Yield (SEY) curve of the material under study, which can be regarded as an electron multiplication factor as a function of the primary energy with which electrons impinge on the dielectric surface. Various methods of obtaining SEY curves have been published, of which those on dielectrics are notoriously challenging [4], given the limitations induced by charging of the (sub)surface region. In this article, we introduce a novel pulsed-beam method specifically

designed for dielectrics, relying only on a hemispherical collector and two identical substrates under study. Surface charging is limited using a μs beam pulse avoiding intermittent discharging.

Electrons impacting a solid material can be backscattered either elastically or inelastically in the material. The latter phenomenon may cause SEE, as the inelastic scattering can be accompanied by emission of secondary electrons from the substrate. The ratio between the total number of electrons released from a material (independent of their energies) and the number of incident electrons is referred to as the total electron emission yield (δ) which is a function of primary energy (E_p):

$$\delta(E_p) = \frac{I_{SE,true}(E_p) + I_{inelastic}(E_p) + I_{BS}(E_p)}{I_p(E_p)} = \frac{I_{SE,tot}(E_p)}{I_p(E_p)} \quad (1)$$

where I_p denotes the primary electron current, I_{BS} the elastic backscattering current, $I_{inelastic}$ the inelastic backscattering current and $I_{SE,true}$ the 'true' current carried by the secondary electrons (SE's) having kinetic energies < 50 eV (the formal definition of SE's). We do not make such a distinction in our measurements and denote the total current from the surface as $I_{SE,tot}$.

Fig. 1 shows a typical SEY curve, where E_{max} indicates the primary energy at which the maximum yield δ_{max} is reached. Two energies exist

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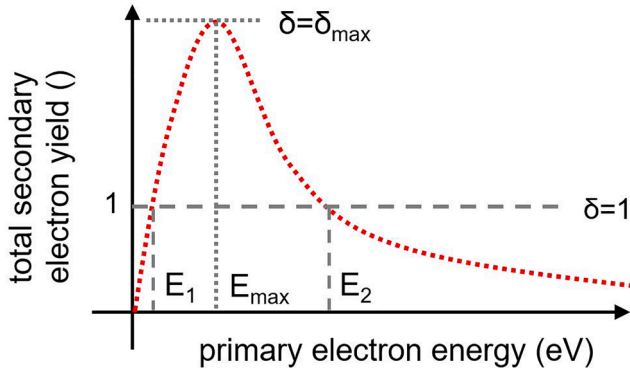
Fig. 1. Schematic total SEY curve, denoting the cross-over energies E_1 and E_2 where $\delta = 1$, as well as the maximum yield δ_{max} at energy E_{max}. Charging of the dielectric inevitably results in flattening of this curve towards the $\delta = 1$ line [4].

where the total SE current equals the primary electron current: the so-called crossover energies E_1 and E_2 at which $\delta = 1$. When δ greater than 1 for non-charged dielectric materials, more electrons are ejected from the material than supplied, which means that holes are generated in the dielectric giving rise to positive charging. Conversely, when $\delta < 1$, the material charges negatively. It has been shown that any dielectric exposed to a continuous electron beam will accumulate precisely the right amount of (sub)surface charge to settle at a stability point, for which $\delta = 1$ [1]. The incoming electron flux then equals the outgoing SE flux and the net charging rate is reduced to zero. Since this happens for any energy, the entire SEY curve effectively flattens for dielectrics under continuous electron irradiation, making the ratio of outgoing to incoming currents equal to unity over the entire energy scale [2].

The main challenges for SEE experiments are formed by substrate charging and by the difficulty to accurately determine the primary current. Charge build-up can be reduced by application of pulsed techniques while surface neutralisation between measurements at various E_p has been achieved by applying either compensation electron pulses at a lower primary energy [5,6], low-energy ion irradiation, laser exposure or substrate heating. However, charge is not localized at the very surface, but distributed throughout the depth of the dielectric substrate, as described by a bilayer model where a penetration depth up to approximately 100 nm (instead of the 10 nm range that is more typical for metals) has been reported [7]. In combination with the slow charge transport in dielectric materials, this distribution of the charge over depth makes it difficult for any neutralisation technique to achieve a reproducible, and truly pristine state in between subsequent SEY measurements and thus complicates the acquisition of the SEY curve for any (hypothetically) uncharged dielectric [8]. Furthermore, even when measuring a surface voltage of 0 V, a sub-surface dipole layer can give rise to an internal electric field affecting the SE emission [2]. Given these intricacies, our strategy is to avoid intermittent discharging at all.

We now propose a novel pulse-based technique where the total SEY is determined for dielectric and other materials, using a single collector only. The collector is part of a 4-grid retarding-field system and we apply primary electron beam pulses with a pulse duration of 2.5 μs. Key to this measurement strategy is that the primary current is obtained from a charge-saturated substrate (at $\delta = 1$) while the SE current is obtained from a pristine substrate (at $\delta \neq 1$). Both are determined by using the same collector and identical electron beam settings. Furthermore, combining the measured δ with I_p, obtained from the measured collector current and corrected for the detection loss factor and for the residual SEE from the collector, we can determine the theoretical surface potential change of the substrate after each measurement point. By ensuring this charging level to stay between -5 and 0 V, with help of a -5 V bias potential, we keep the effects of surface charging limited without the need of further intermittent discharging measures. In the following, we present the experimental apparatus and illustrate our

approach with measurements on alkali-free glass.

2. Material and methods

2.1. Experimental

The experiments were conducted in the ROSA-SEY setup at ARCNL with a UHV working pressure $< 10^{-8}$ mbar, comprising three sections: 1) substrate loading, 2) analytical tools and 3) thin film deposition. The system has a separate load lock in order to introduce substrates in the experimental chamber without breaking vacuum. Samples are clamped to a Mo back plate that serves as part of the sample holder. The sample holder is mounted on a manipulator mechanism that enables linear transfer throughout all sections of the ROSA-SEY system. The sample holder is provided with two off-axis sample positions. In one position, samples can be heated to 1000 °C. By rotation of the sample holder, two samples at a time can be linearly positioned and rotated with respect to the incoming electron beam. A schematic overview of the SEY-part of the setup is provided in Fig. 2.

We use a LEG 22 electron gun [9] to generate primary electrons in the range 0.3–2.5 keV. The collector is part of a 4-grid Vacuum Generators 640 Retarding Field Analyzer (RFA) system [9], covered by a thick soot layer to suppress SEE of its own. A shielded cable connects the collector to a variable-gain high-speed current amplifier (DHPCA-100, Femto [10]), featuring transimpedance amplification at 10^6 V/A. The retarding potential and resulting collector current can automatically be scanned using software designed for Auger electron spectroscopy. For our SEY measurements of dielectrics, the RFA has not been used for scanning and the grids were connected to ground potential.

To convert the measured collector current to the actual SE current from the sample, two corrections must be made. Firstly, each grid transmits only 82 % of the electrons, based on its optical transparency [11]. The stack of four grids consequently yields a total current transmission fraction of $\alpha = (0.82)^4 = 0.45$. Secondly, the SEE of the collector itself needs to be accounted for. We found that 99 % of secondary electrons emitted by the collector have energies below 30 eV and that the current loss that these secondary electrons caused, from the collector to the nearest grid, can be accounted for by multiplying the measured collector current by a correction factor of $\eta = 1.58$, independent of the primary electron energy E_p. This number was obtained by comparing the collector current in non-biased conditions to the collector current as a function of positive collector bias voltage up to 30 V for each of the
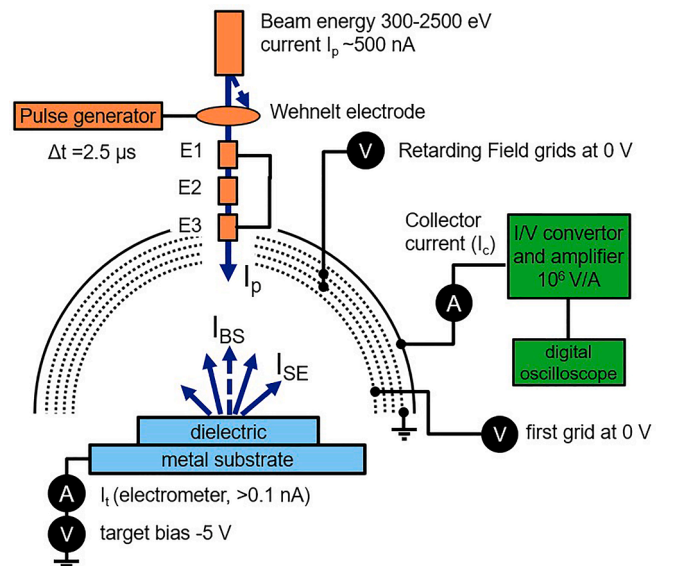

Fig. 2. Schematic overview of the collector-only SEY measurement setup.

primary energy points.

In the experiments that we present here, we used alkali-free glass of 0.8 mm thickness for both samples. For our purpose, a thin sample is to be preferred, as it maximizes the capacitance and minimizes the potential build-up on the surface. Before introduction in the experimental setup, the stack of sample and Mo backplate was dipped in Isopropyl Alcohol (IPA) while remaining electrically connected to ground potential via a wire, in order to clean and discharge the dielectric surface.

The primary electron beam was pulsed by a ring-shaped Wehnelt electrode. This was realized by connecting a pulse generator to a transformer, feeding the Wehnelt potential. A pulse duration of 2.5 µs was empirically chosen such that it is short enough to avoid excessive surface charging, while being sufficiently long to ensure a flat-top electron current to be measured. In addition, the short pulse duration aids in limiting radiation-induced contamination of the surface. The applied pulse frequency was 1 kHz. The data obtained at the collector were stored by a Keysight (100 MHz InfiniiVision DSOX2012A) digital oscilloscope [12]. Prior to SEY measurements, we verified that the electron beam spot was fully located on the dielectric surface. An easy way to verify this was to check that the leakage current was well below 0.1 nA, even at a total beam current of 500 nA.

2.2. Theory

Provided that the sample leakage current (I_t) is negligible, for dielectrics charged to saturation, the SE current, which is measured by the collector, becomes equal to the primary current. In short: $I_p = I_{SE} = I_c$, if $\delta = 1$ and $I_t = 0$, where I_c is the collector current (where transmission loss factors are omitted for simplicity). Now consider an uncharged or minimally charged dielectric, for which $\delta \neq 1$. In this case: $I_{SE} = I_c \neq I_p$. In either case, the same fraction of electrons is captured by the grids (α), assuming no dependency on the electron energy in the range $0 < E_{SE} < E_p$. Including now also the SE correction factor at the collector (η), we obtain the following expression for the total SEY:

$$\delta_{tot}\left(E_p\right) = \frac{I_{SE}\left(E_p\right)}{I_p\left(E_p\right)} = \frac{\left(\frac{\eta}{\alpha}\right)I_{c,0}\left(E_p\right)}{\left(\frac{\eta}{\alpha}\right)I_{c,\infty}\left(E_p\right)} = \frac{I_{c,0}\left(E_p\right)}{I_{c,\infty}\left(E_p\right)} \quad (2)$$

where $I_{c,0}$ denotes the collector current at $t=0$, i.e. on an uncharged sample, and $I_{c,\infty}$ denotes the collector current at $t \gg 1$ s, i.e. for a fully charged sample. It is clear that the total electron correction factor η/α cancels out when taking the ratio of both collector currents, making this approach calibration independent. Equation (2) relies on the SEY being unity for fully charged conditions, which requires the sample leakage current to be much lower than the primary (or collector) current. This condition is usually satisfied for dielectric materials. When this is not the case, e.g. when measuring on semiconducting or conductive materials, the sample leakage current should be measured and added to the denumerator $\left(\frac{\eta}{\alpha}\right)I_{c,\infty}\left(E_p\right)$. Unfortunately, in that case, one cannot take advantage of the cancellation of the correction factors η/α. Here, we restrict ourselves to the case of dielectric materials.

To determine the primary current for primary energy E_p, one of the two samples was always deliberately charged to the stability point using a continuous primary current, fulfilling $\delta = 1$. The pulsed collector current of the electrons released from this charge-saturated substrate $I_{c,\infty}$ was then acquired, as a measure for the primary beam current during a pulse. After this, the primary beam was shut off and the pristine substrate was rotated into the measuring position in order to measure $I_{c,0}$ as a measure for the SE current. According to Eq. 2, we then simply obtained δ at that primary energy as the ratio between these two measured currents.

Note that at this point we have not applied any active charge mitigation strategy for either of the two samples, between different settings of the primary energy E_p. Using I_p and δ, we can calculate the amount of surface charging during the experiment. At each primary energy E_p, we

simply multiply the primary current I_p by the pulse duration t_p, the number of pulses N_p, the inverse capacitance C and take into account how much δ deviates from unity:

$$\Delta V_{s,E_p} = (\delta - 1)t_p N_p\left(\frac{\eta}{\alpha}\right)I_{c,0}C^{-1} = (\delta - 1)t_p N_p\left(\frac{\eta}{\alpha}\right)I_{c,0}\left(\frac{d}{\varepsilon_0\varepsilon_r A}\right) \quad (3)$$

In this equation, we approximate the capacitance by assuming an (infinite) parallel plate geometry with the thickness d of the dielectric layer serving as the plate separation and the spot size A as the area. The vacuum and relative permittivity of the dielectric are indicated by ε_0 and ε_r, respectively.

Using Eq. 3, we kept track of the potential rise per primary energy measurement $\Delta V_{s,E_p}$ on top of the -5 V bias level, as well as the cumulative amount per experimental run, determined by the number of E_p values per SEY curve. As soon as the total potential rise $\Delta V_{s,tot} = -5 + \sum \Delta V_{s,E_p} > 0$ V, the experiment should be terminated. The -5 V bias level was chosen such as to offset positive charging, while remaining low enough not to affect the incidence energy of the primary electrons by more than 5 eV. For cases of $\Delta V_{s,tot} > 0$, the surface charging would make it impossible for the lower-energy electrons to escape the material, thereby noticeably affecting the SEE and thus influencing the measured SEY. Note that Eq. 3 provides an upper estimate for the charging effect, as it does not account for charge leakage during the experiment, either discharging the sample, or redistributing charges laterally, out of the area of the beam spot. The alkali-free glass that was used as the test material in this work is highly insulating, with a volume resistivity of 7×10^{18} Ωm, while the experiment is carried out within a few hours. Charge leakage is therefore negligible for this material.

3. Results

Fig. 3 shows two curves. The black, solid curve is the average of three current pulses measured on the collector from a fully charged alkali-free glass sample ($I_{c,\infty}$) at a primary electron energy of 300 eV and a pulse duration of 2.5 µs. The red, dashed curve is the average of two pulses on a non-charged, but otherwise equal dielectric material that was exposed to similar pulses. The sample thickness d was 0.8 mm and the beam diameter was 6 mm. The thin dashed vertical lines at $t = -1.5$ µs and $t = -0.15$ µs indicate the time window over which the average pre-pulse baseline was measured. Similarly, the thin dashed lines at $t = 1.06$ µs and $t = 2.38$ µs indicate the time window for the measurement of the average pulse signal.

It was empirically verified that the oscillatory signal distortion observed during the first 1 µs after the start of each pulse and during the first 1 µs after the end of each pulse can be linked to transient-induced ringing. This is caused by electromagnetic crosstalk between the internal wiring of the grids and the collector geometry due to parasitic inductances and capacitances. Thanks to the transient nature of this ringing, the signal beyond 1.06 µs after applying the pulse is considered to be sufficiently representative for the total SE current. The average level at $t < 0$ µs, i.e. prior to the electron pulse, represents the near-zero background collector current, which we also measure and subtract from the measured average current during the pulse.

In Fig. 3 one readily recognizes that during the electron pulse for both samples, the collector current I_c differs from the baseline level. For this, we focus on the time frame after the transient ringing, at times of $1.06 < t < 2.38$ µs, during which, apart from measurement noise, the current signal is constant in time. One can also recognize directly that the collector current levels on the pristine and charge-saturated samples are significantly different. The ratio between the averaged ΔI_c measurements on the pristine sample and the reference sample provides a value for δ of 2.26 ± 0.64 at this specific primary energy of 300 eV. Repeating this procedure for several primary energies in the range $0 < E_p < 2.5$ keV, we obtained the SEY curve of alkali-free glass, shown in
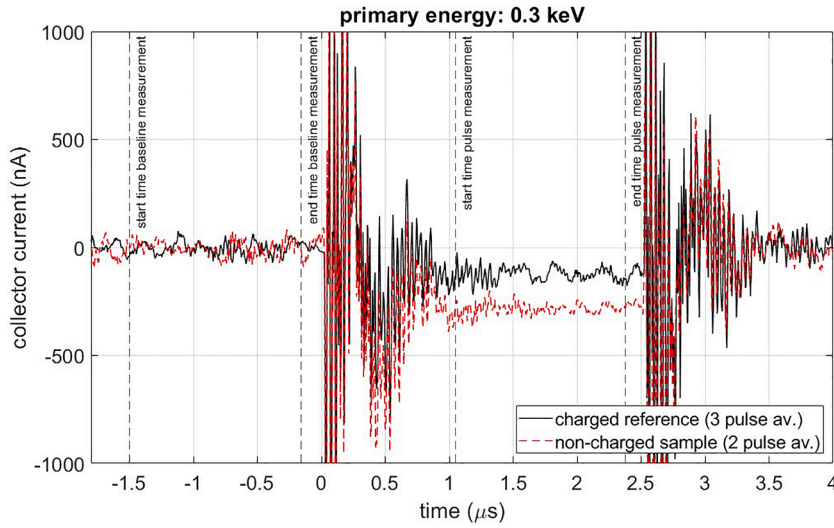
Fig. 3. SE current pulses measured on the collector, emanating from a fully charged alkali-free glass sample ($I_{c,\infty}$, black solid curve) and an equal non-charged sample ($I_{c,0}$, red dashed curve). The primary electron energy was 300 eV in both cases and the pulse duration was 2.5 µs. Thin vertical dashed lines indicate the time windows over which the pre-pulse baseline and the pulse signal were measured. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
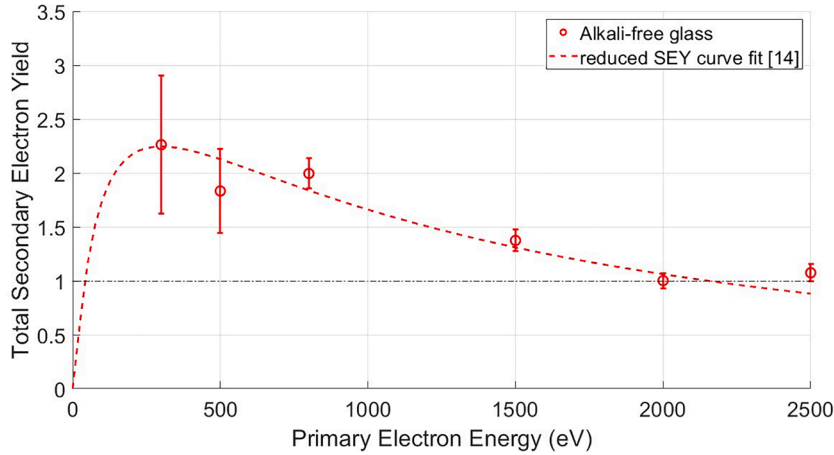

Fig. 4. SEY curve of alkali-free glass, experimentally determined in the ROSA-SEY setup, following the measurement procedure as described in the text. The number of experimental points is limited by surface charging constraints which are assessed using Eq. 3. The grey dash-dotted line represents the condition $\delta = 1$ and the red dashed curve is a Gauss fit in the logarithm of E_p/E_{max} (reduced δ curve [14]), Eq. 4. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 4.

The Mo support plate on which the samples were clamped was biased to −5 V in order to offset the (positive) charging during this experiment [13]. Each data point in Fig. 4 results from the average of two identical SE pulses of 2.5 µs each, while $I_{c,\infty}$ is determined by averaging three pulses. The total error comprises the statistical error following from propagating the standard deviations in the signals $I_{c,0}$ and $I_{c,\infty}$ evaluated over the time windows indicated in Fig. 3, as well as a systematic error. The latter originates from a 5 % drift at maximum in the electron beam current between the reference measurement and the SE measurement, due to small changes of the vessel pressure. Secondly, as the total surface potential became slightly larger than 0 V during the measurement at 500 eV and 300 eV subsequently (see Table 1 below), an extra error of 10 % and 15 % respectively was accounted for those points.

From the limited dataset shown in Fig. 4 we find $\delta_{max} = 2.26 \pm 0.64$, $E_{max} = 300$ eV and $E_2 = 2100$ eV (the second cross-over point at which $\delta = 1$). These numbers can be used to construct a 'reduced δ curve', which is an expression that links $\delta(E_p)/\delta_{max}$ to E_p/E_{max} using a Gaussian distribution in the logarithm of E_p/E_{max} [14]:

$$\delta_G(E_p) = \delta_{max} \cdot exp\left(- \left[\ln\left(\frac{E_p}{E_{max}} \right) \right]^2 \Big/ 2\sigma^2 \right) \tag{4}$$

Table 1

Overview of data for the SEY curve of Fig. 4 and the degree of surface charging accumulated during these measurements. Two electron beam pulses were used ($N_p = 2$) per primary energy value. From left to right, the columns represent the primary electron energy, the order in which the measurements were acquired, the uncorrected value of the measured primary current, the 'true primary current' (corrected for grid absorption and collector SEE), the uncorrected value of the measured SE current, the total SEY (δ), the charge 'injected' in the surface per electron pulse, the potential change on the surface per electron pulse and the final column shows V_s prior to applying the first pulse at E_p, taking the −5 V sample holder bias into consideration.

E_p (keV)	Meas. order	$I_{c,\infty}$ (nA)	I_p (nA)	$I_{c,0}$ (nA)	δ	Charge / pulse (pC)	Potential rise / pulse ΔV_s (V)	V_s before pulse (V)
0.3	6	122.6	428.5	277.4	2.26	1.35	0.85	2.55
0.5	5	275.4	962.4	504.7	1.83	2.00	1.26	0.04
0.8	4	349.7	1221.9	697.6	2.00	3.04	1.90	−3.77
1.5	3	270.0	943.6	371.1	1.37	0.88	0.55	−4.88
2.0	2	204.5	714.7	205.0	1.00	4.37E-3	0.00	−4.88
2.5	1	144.1	503.6	154.9*	1.07	9.44E-2	0.06	−5.00

* Only second pulse used to determine collector current.

where σ codes for the width of the distribution. This equation has been found to fit SEY datasets of different materials rather well for E_p greater than 100 eV [5], but a physical basis for this functional form is still lacking. The best fit is shown in Fig. 4 as the dashed red curve with $\sigma = 1.55$.

Since δ deviates significantly from unity for a large part of the curve, SE-induced surface charging is a point of attention. To assess this, the potential rise per energy point, starting from 2.5 keV in the experiment, is calculated using Eq. 3. The result is shown in column 8 of Table 1 as well as the total accumulated surface potential in column 9. As can be seen, the beam-induced surface potential prior to the last pulse pair at 300 eV is + 2.55 V, when taking the −5 V sample bias into account. Hence, only during the measurement at this last E_p, sample charging is likely to have affected the SEY and the experimental run was terminated. The measurement points ranging 0.5 to 2.5 keV are however deemed reliable.

When the total, accumulated charging potential has become too high, the sample can be discharged manually using dipping in IPA, after which the measurement can be continued, for instance to closely asses the range $300 < E_p < 500$ eV in order to achieve a more accurate determination of E_{max} and δ_{max}.

Finally, the first cross-over point E_1 is of great interest. Unfortunately, this point cannot be addressed directly using the ROSA-SEY setup as the required primary energies required are too low (<100 eV) for the setup in its present configuration. Analytically, this low-energy regime of the SEY curve can be extrapolated from the higher-energy measurements, by making use of the three-dimensional constant-loss theory developed by Dionne [15], from which one obtains the following expression for E_1:

$$E_{1,D} = 0.51 \cdot E_{max} \cdot \delta_{max}^{-1.32} \tag{4}$$

In this way, we obtain $E_{1,D} = 52$ eV for the case of alkali-free glass. For a more precise estimate, more accurate values should be obtained for δ_{max} and E_{max}, e.g. by acquiring more data points around 300 eV primary energy.

4. Discussion

The shape shown in Fig. 4 for the SEY curve obtained on alkali-free glass, with $\delta_{max} = 2.26 \pm 0.64$, $E_{max} = 300$ eV and $E_2 = 2100$ eV, matches the expectation of a curve dictated by SE physics (as in Fig. 1), and the absolute magnitude range of δ falls within the range of other glass types found in the literature [4]. The total SEE-induced surface charging should remain below +5 V, so that in combination with the applied sample holder bias voltage of −5 V, the maximum potential does not exceed 0 V. As Table 1 shows, the summation over all potential changes due to the injected surface charge resulted in a net potential of +2.55 V (including the −5 V bias) at the final primary energy value in the series of six measurements at different primary energies. Prior to applying the final pulse pair at $E_p = 300$ eV, the net potential already amounted to +2.55 V, which has likely disturbed this SEY measurement somewhat, since this net positive surface potential must have pulled a fraction of the secondary electrons back to the sample surface, thus reducing the measured value of δ. An additional, accumulative effect is that of local depletion of electrons, which may occur in the dielectric material over the course of multiple measurements. Also this effect should be expected to lower the SEY. In order to track the influence of these factors, it is recommended to perform each measurement of a SEY curve on an identically prepared surface twice: once starting at high E_p-values and stepping to lower primary energies, as we did here, and once starting at low E_p and stepping up the energy. If charging and electron depletion effects are sufficiently modest, the two measured curves should ideally overlap, possibly with a minor deviation in each curve only at the final energy point (the tails of the two SEY curves on either end).

In addition, a few simple improvements can be made to reduce

surface charging per pulse, as is readily recognized by examining Eq. 3. To this end, one can decrease the primary current, decrease the pulse duration, decrease the sample thickness and increase the diameter of the primary beam spot. The first two of these are ultimately limited by considerations of the signal-to-noise ratio (SNR) of the integrated/averaged SE current. As discussed earlier, our setup allows switching between Auger electron spectroscopy and SEY measurements. Apart from the diagnostic advantage, it has the drawback that four RFA grids are present in the latter case that reduce the collector current level by 55 %, thereby compromising our SNR. As different materials may exhibit lower or higher SEY values compared to the present example of alkali-free glass, the trade-off between beam current, pulse duration, number of measurement points and SNR needs to be experimentally determined each time.

Based on this discussion and taking note of the 'disclaimer' that the sixth energy point may have to be discarded due to charging, but that the first five did not suffer from such effects, we conclude that it is feasible to experimentally determine a SEY curve using the setup and measurement procedure described here. The presented SEY curve that we obtained on alkali-free glass in this fashion comprised data at six different primary energies (where charging may have affected the one at $E_p = 300$ eV somewhat), with two separate pulses acquired at each primary energy, from which δ was evaluated. Despite the limited number of primary energy values per run, the advantages of the new SEY measurement method, described here, are apparent. Firstly, apart from the need for a UHV chamber and a configurable electron gun, the hardware configuration is simple, as it relies only on a single collector that can even be part of a traditional Auger electron spectroscopy RFA system. Secondly, no calibration procedure is required, both with respect to the incident beam characteristics and with respect to the detection efficiency. Thirdly, no intermittent surface discharging procedure has to be applied, which enables one to completely avoid possible chemical changes to the surface that may result from ion beam exposure as well as the intricacies of apparent surface charge removal while a subsurface charge dipole may still remain present [1].

5. Conclusions

Measurements of the SEY of dielectrics based on a novel collector-only method were demonstrated to be feasible. A SEY curve of alkali-free glass was presented, comprising a series of five reliable SEY measurements at different primary energies obtained in a single experiment. The method relies on the application of two identical substrates of which one is used in the charge-saturated condition, to measure the primary current, while the sample under investigation is kept at charging levels that are low enough to ensure undisturbed measurements of the SE current. By determining ratios between measured currents, we make this approach completely calibration free. Each experimental run is terminated once the SE-induced positive surface charging exceeds a pre-set sample bias voltage of −5 V and leads to a net positive potential. The charging level is easily determined from the beam parameters and the measured values of the SEY. The low charging levels at which this technique operates completely removes the need for intermittent discharging protocols and thus avoids potential problems arising from altered surface chemistry, caused by active discharging procedures and from residual internal charges that may be left after surface neutralization, in both cases introducing undesired changes to the SE physics.

CRediT authorship contribution statement

Gustaaf van Eden: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Duncan Verheijde:** Resources. **Jan Verhoeven:** Conceptualization, Methodology, Investigation, Resources.

Declaration of Competing Interest

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