A New Fit to Secondary Emission Yield in the Low Impact Voltage Regime: An Improvement of Vaughan's Expression

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Abstract

Reducing the emission of secondary electrons from materials is critical to improved efficiency and increased performance in high power vacuum electronics. A new mathematical expression for the secondary emission yield (SEY) as a function of the impact voltage up to a maximum of 5 kilovolts is proposed which is an extension of a formula first suggested by Vaughan. The new analytical fit and Vaughan's fit are compared with SEY experimental data reported by others and measured by our group. The new analytical expression gives good fits to SEY experimental data in all cases, even when the SEY maximum is either slightly larger or below unity, two situations for which Vaughan's fit is either inadequate or inapplicable.

1 Introduction

When electrons strike a material, there is a probability that a secondary electron will be emitted from its surface. For this to occur, the secondary electron must migrate towards the surface and have sufficient energy to leave the material. The number of secondary electrons emitted per incident electron is referred to as secondary emission yield (SEY) [1–8]. Modeling of SEY versus impact voltage has been performed for a long time [1–6], using Monte Carlo simulations [9–14] and development of semi-empirical models [15–17]. Over the years, there have been several proposals for semi empirical formulae to fit SEY experimental data [15–19]. For instance, Vaughan proposed an empirical formula to fit SEY data over a range of low impact voltage regime, i.e., which he tested with data up to a maximum of 2.25 kilovolts [18]. This method requires the knowledge of three critical points in the SEY data, including the values of the impact voltage where the SEY reaches unity on both sides of the SEY maximum (which must be obtained by extrapolation of SEY measurements), as well as the value of the impact voltage at which the SEY reaches a maximum. For Vaughan's fit to work, the SEY maximum must be greater than unity (around 1.3 or above), as will be shown in section 4. For the sake of comparison with the new SEY fit proposed in this paper, we first briefly describe Vaughan's analytical fit.

The formula proposed by Vaughan for the SEY (δ) is as follows:

$$\frac{\delta}{\delta_{max}} = (ve^{1-v})^k, \tag{1}$$

where δ_{max} is the SEY max, v is the normalized incident electron impact voltage:

$$v = \frac{V_i - V_0}{V_{max} - V_0}, \tag{2}$$

where V_0 is the threshold voltage (i.e., the impact voltage at which δ rises abruptly when the

incident electron has sufficient energy to generate secondary electrons), V_i is the impact voltage, and V_{max} is the value of the impact voltage where δ_{max} occurs.

In Eq.(1), k is a fitting parameter that must be estimated using the SEY experimental data. Equation (1) agrees with the experimental data at the SEY maximum. In Vaughan's approach [18], the value of k is selected so that Eq.(1) agrees with the SEY experimental data at two additional impact voltage values: the impact voltages below (v_1) and above (v_2) the SEY maximum at which the SEY is equal to unity, as illustrated in Figure 1 (the values of v_1 and v_2 may have to be determined by extrapolation of measured SEY data). As shown by Vaughan [18], this can be achieved with Eq.(1) if the following smooth variation of the fitting parameter k is used:

$$k = \frac{k_1 + k_2}{2} - \frac{k_1 - k_2}{\pi} arctan(\pi ln(v)), \tag{3}$$

where k_1 and k_2 are given by:

$$k_{1,2} = ln\left(\frac{\delta_{max}}{v_{1,2} - ln(v_{1,2}) - 1}\right). \tag{4}$$

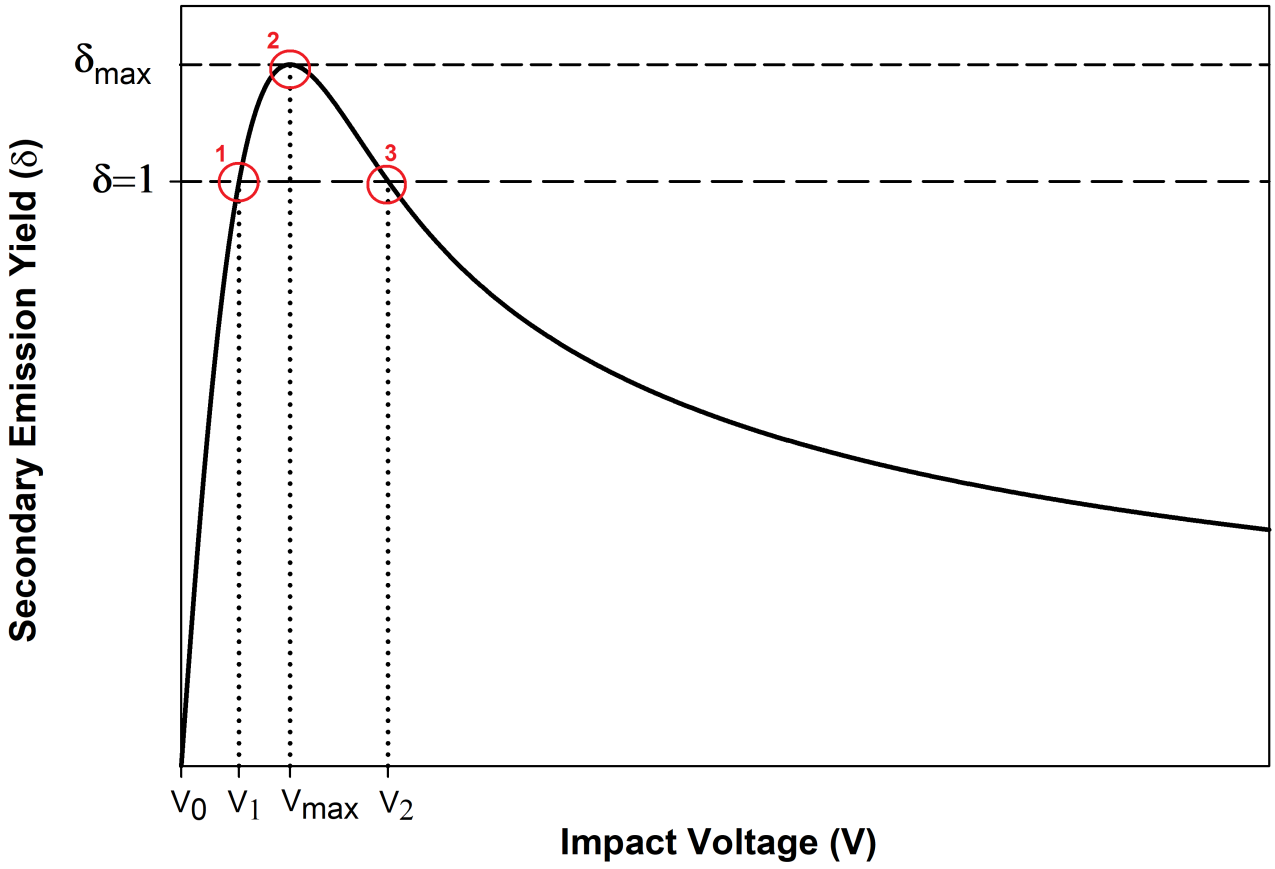

FIG. 1. (Color online) Schematic representation of impact voltage dependence of SEY data. In Vaughan's approach, three critical points are used to fit SEY experimental data: the location of the SEY maximum and the two values of the impact voltage at which the SEY (delta) reaches unity. These two values are labeled v_1 and v_2 below and above the SEY maximum, respectively. The values of the impact voltage are normalized using Eq.(2). In these units, the SEY maximum occurs at v_{max}.

Vaughan's fit [18] works well for SEY data with δ_{max} at about 1.3 or above but becomes less accurate for impact voltages larger than 3 times V_{max}. As will be shown in section 4, as δ_{max} approaches unity, Vaughan's fit is only accurate near the SEY maximum. By construction,

Vaughan's fit cannot be applied when δ_{max} drops below unity.

In the next section, we extend Vaughan's approach and propose a new empirical fit to SEY data which is not only applicable for SEY data with maxima below unity, but also provides a good fit in the entire impact voltage range above V_{max} for SEY data taken up to 5 keV.

2 Improved Vaughan Fit

The proposed new SEY fit requires the knowledge of five critical points in the SEY experimental data, which include the location of the SEY maximum, and two extra points both below $(V_{\alpha}^{L}, V_{\beta}^{L})$ and above $(V_{\alpha}^{H}, V_{\beta}^{H})$ the SEY maximum, as illustrated in Figure 2. Due to the dynamic nature of the selection of these critical points, the new fitting method can be applied to fit a large amount of SEY data, as will be shown in section 4.

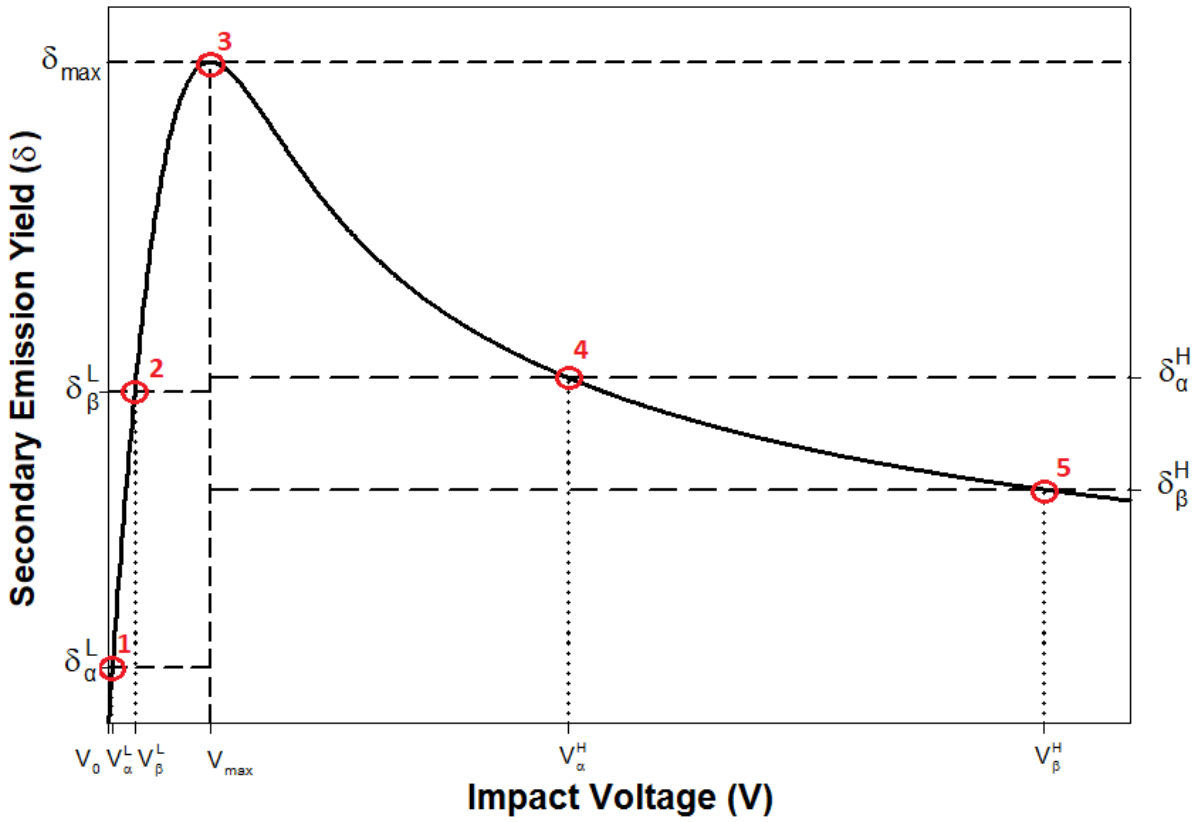

FIG. 2. (Color online) Location of the five critical points selected to perform a fit to a set of SEY experimental data. The improved Vaughan fit requires knowledge of 5 critical points including the location of the SEY maximum, two SEY values below the SEY maximum, and two SEY values above the SEY maximum (points 1 through 5). The superscripts L and H correspond to data below (V_α^L, V_β^L) and above (V_α^H, V_β^H) the location of the SEY maximum, V_{max}, respectively.

The new fit to SEY data is based on the following empirical formula which is a generalization of Vaughan' expression:

$$\frac{\delta}{\delta_{max}} = v^{k_1} e^{(1-v)k_2}, \tag{5}$$

where the values of the fitting parameters for k_1 and k_2 are found by imposing that Eq.(5) agrees

with the SEY data at the two selected impact votlages below (v_α^L, v_β^L) and above (v_α^H, v_β^H) the SEY maximum, as shown in Figure 2. These values are dynamically selected until the best least mean square (LMS) fit between Eq.(5) and the SEY data over the recorded range of impact voltage is reached. Starting with Eq.(5) and Figure 2, it can be shown that the values of the fitting parameters below ($k_{1,2}^L$) and above ($k_{1,2}^H$) the SEY maximum are given by:

$$\begin{aligned}
k_1^L &= \frac{(1-v_\beta^L)ln(\delta_\alpha^L/\delta_{max}) - (1-v_\alpha^L)ln(\delta_\beta^L/\delta_{max})}{(1-v_\beta^L)ln(v_\alpha^L) - (1-v_\alpha^L)ln(v_\beta^L)}, \\
k_2^L &= \frac{ln(v_\beta^L)ln(\delta_\alpha^L/\delta_{max}) - ln(v_\alpha^L)ln(\delta_\beta^L/\delta_{max})}{(1-v_\alpha^L)ln(v_\beta^L) - (1-v_\beta^L)ln(v_\alpha^L)}, \\
k_1^H &= \frac{(v_\alpha^H-1)ln(\delta_\beta^H/\delta_{max}) - (v_\beta^H-1)ln(\delta_\alpha^H/\delta_{max})}{(v_\alpha^H-1)ln(v_\beta^H) - (v_\beta^H-1)ln(v_\alpha^H)}, \\
k_2^H &= \frac{ln(v_\alpha^H)ln(\delta_\beta^H/\delta_{max}) - ln(v_\beta^H)ln(\delta_\alpha^H/\delta_{max})}{(v_\alpha^H-1)ln(v_\beta^H) - (v_\beta^H-1)ln(v_\alpha^H)},
\end{aligned} \tag{6}$$

where the values for $\delta_{\alpha,\beta}^{L,H}$ are varied as a function of the fitting parameters $\Gamma_{\alpha,\beta}^{L,H}$ using

$$\delta_{\alpha,\beta}^{L,H} = \delta_{min}^{L,H} + \Gamma_{\alpha,\beta}^{L,H}(\delta_{max} - \delta_{min}^{L,H}), \tag{7}$$

where $\delta_{min}^{L,H}$ are the measured minimum SEY data points below and above v_{max}, respectively.

These values of $\Gamma_{\alpha,\beta}^{L,H}$ are dynamically selected until the best LMS fit between Eq.(5) and the SEY data over the recorded range of impact voltage is reached. For most experimental SEY data, it is very unlikely to have data points exactly at the four values of the impact voltages v_α^L, v_α^H, v_β^L, and v_β^H (associated with the dynamically selected value of $\delta_\alpha^L, \delta_\alpha^H, \delta_\beta^L, \delta_\beta^H$, respectively) leading to the optimal LMS fit. In this case, the values of v_α^L, v_α^H, v_β^L, and v_β^H, must be obtained using linear interpolation between available SEY experimental data using the following procedure:

$$v_{\alpha,\beta}^{L,H} = v_a + \frac{(v_b - v_a)}{(\delta_b - \delta_a)}(\delta_{\alpha,\beta}^{L,H} - \delta_a), \tag{8}$$

where δ_a (δ_b) is the SEY data point closest and, respectively, below (above) the needed critical point in the LMS fit and v_a (v_b) is the corresponding impact voltage.

To fit a given set of SEY experimental data, the values of $\Gamma_{\alpha,\beta}^{L,H}$ were swept across the following ranges until the optimum fit was found: $\Gamma_{\alpha}^{L,H}$ was swept from 0.001 to 0.099, while $\Gamma_{\beta}^{L,H}$ was swept from 0.1 to 0.99. In order to numerically determine the best values of the parameters of $\Gamma_{\alpha}^{L,H}$ and $\Gamma_{\beta}^{L,H}$, an LMS algorithm was implemented. This algorithm independently calculated LMS values for data points below and above v_{max} to determine $\Gamma_{\alpha,\beta}^{L}$ and $\Gamma_{\alpha,\beta}^{H}$, respectively. Numerical values of the fitting parameters $\Gamma_{\alpha,\beta}^{L}$ and $\Gamma_{\alpha,\beta}^{H}$ for a wide range of materials are given in section 4.

Similar to approach suggested by Vaughan, the following expression is used:

$$k_{1,2} = k_{1,2}^{H} + \frac{(k_{1,2}^{L} - k_{1,2}^{H})}{1 + e^{(v-1)/0.05}}, \tag{9}$$

to allow a smooth transition of the values of k_1 and k_2 from below ($k_{1,2}^{L}$) to above ($k_{1,2}^{H}$) the SEY maximum.

Before comparing Vaughan's expression (Eq. 1) and its proposed modified version (Eq. 5) to SEY experimental data, we briefly describe in the next section the experimental setup used in the Materials and Manufacturing Directorate at Wright Patterson Air Force Base to measure SEY data on various samples.

3 Experimental SEY Measurements

Figure 3 shows a diagram of the experimental setup we used to measure SEY data of various targets.

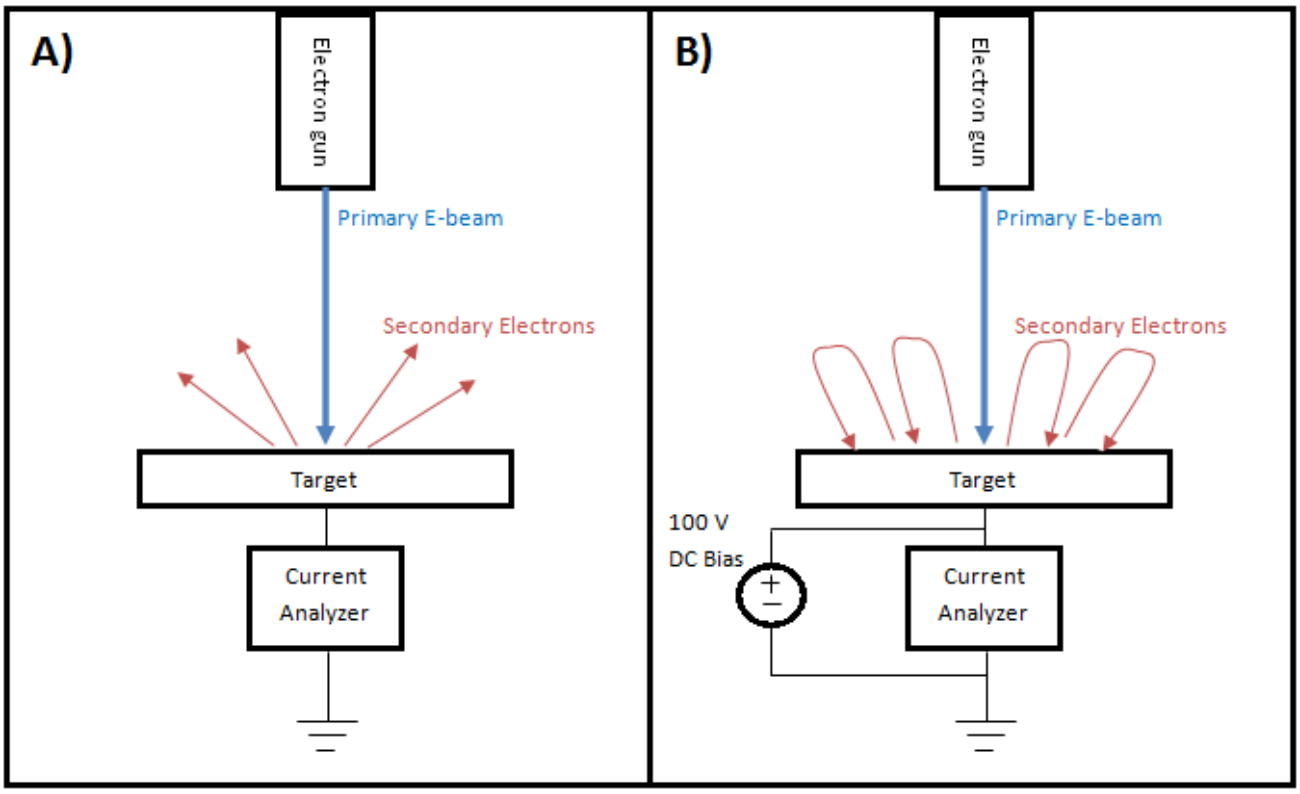

FIG. 3. (Color online) Diagram of experimental setup to record SEY data of various materials.

This setup uses a two step process to make SEY measurements. In the first step (Figure 3a), the electron gun is first directed towards the target with a given energy. The current that flows from the target to ground is then recorded. This current represents absorbed electrons that were not re-emitted or backscattered. In the second step (Figure 3b), a positive DC voltage bias is applied to the target and a second current value is recorded. The energy of the incident electron beam is reduced proportionally to the DC bias voltage to compensate for the additional kinetic energy from the bias voltage. This new current now represents all absorbed electrons in addition to low energy secondary emitted electrons that now cannot escape the electric field generated from the DC voltage source. Secondary electrons have typically very low energy so

a DC bias of 100 V, which would retain all electrons under 100 eV, successfully captures almost all the secondary electrons. This process neglects any re-emitted electrons with an energy greater than 100 eV and all backscattered electrons.

After both current values are recorded, the SEY can be calculated as the ratio of the re-emitted electron current to the total current. Total current can be estimated by the current produced from the bias ON state, while re-emitted current can be estimated with the current from the bias OFF state subtracted from the current from the bias ON state. This results in the following simple formula used to calculate the SEY:

$$\delta = \frac{I_{ON} - I_{OFF}}{I_{ON}}, \tag{10}$$

where the current from the DC bias ON and OFF conditions is given by I_{ON} and I_{OFF}, respectively.

The setup shown in Figure 3 takes place in a vacuum chamber that is consistently kept under a pressure of 10^{-8} Torr. The electron beam used could be accelerated up to a max electron kinetic energy of 5 keV. A more detailed discussion of SEY measurement methodology is discussed by Kirby [20]. Most SEY data taken using the technique described above had an energy range from 100 to 5000 eV. In our experiments, we measured the SEY at 5 different locations in the low impact voltage regime, i.e., below and around V_{max}, and at 5 other locations (from 1 to 5 kV, in steps of 1kV) above V_{max}. To test the validity of the new SEY fit proposed in this paper, some of the SEY data points modeled in the next section were taken from the literature, with most plots containing about 10 experimental SEY data points with the 5kV range investigated hereafter.

4 Results

The extension of Vaughan's fit was tested on multiple SEY data sets and compared with Vaughan's original fit. Figures 4 through 13 show fits to SEY data for various samples, where the modified Vaughan fit (Eq. 5) works excellently up to 5 keV. The value of the threshold voltage V_0 in all these fits was set equal to 0 and found to be fairly insensitive to its exact value. Tables (I-III) show all the parameter details for the samples covered in this work. Any SEY data provided by our group used the measuring technique describe above in section 3. The figures are ordered from highest to lowest SEY maximum data.

4.1 Materials with SEY data with maximum above 1.3

Figures 4 through 6 show data with SEY maxima above 1.3. For those cases, Vaughan's fit (Eq. 1) follows the SEY curve relatively well up to about $3V_{max}$. However, the SEY data in Figure 4 does not contain the SEY unity intersection in the high impact voltage regime required for Eq.(1) to work, thus only Eq.(5) can be used in thise case.

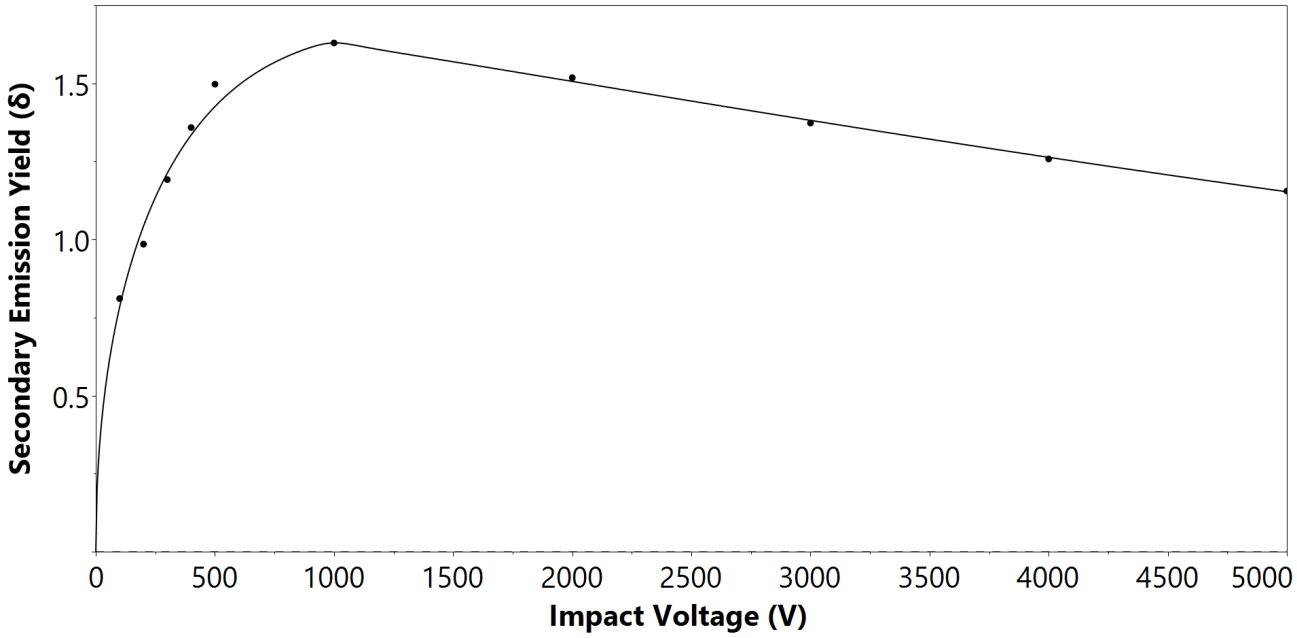

FIG. 4. Modified Vaughan fit (Eq. 5) to SEY data collected by us on a Au sample. The original Vaughan fit is not shown since no experimental data points for which $\delta = 1$ on the high impact voltage side was measured.

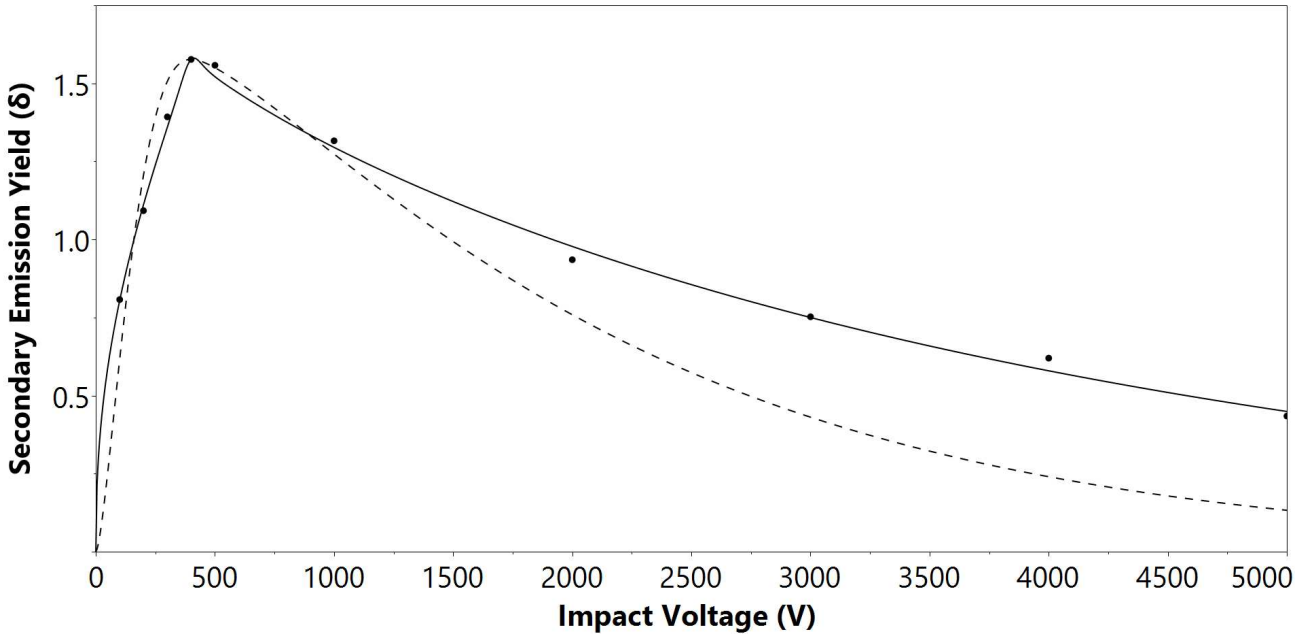

FIG. 5. Modified Vaughan fit (solid line, Eq. 5) versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on a Ni sample.

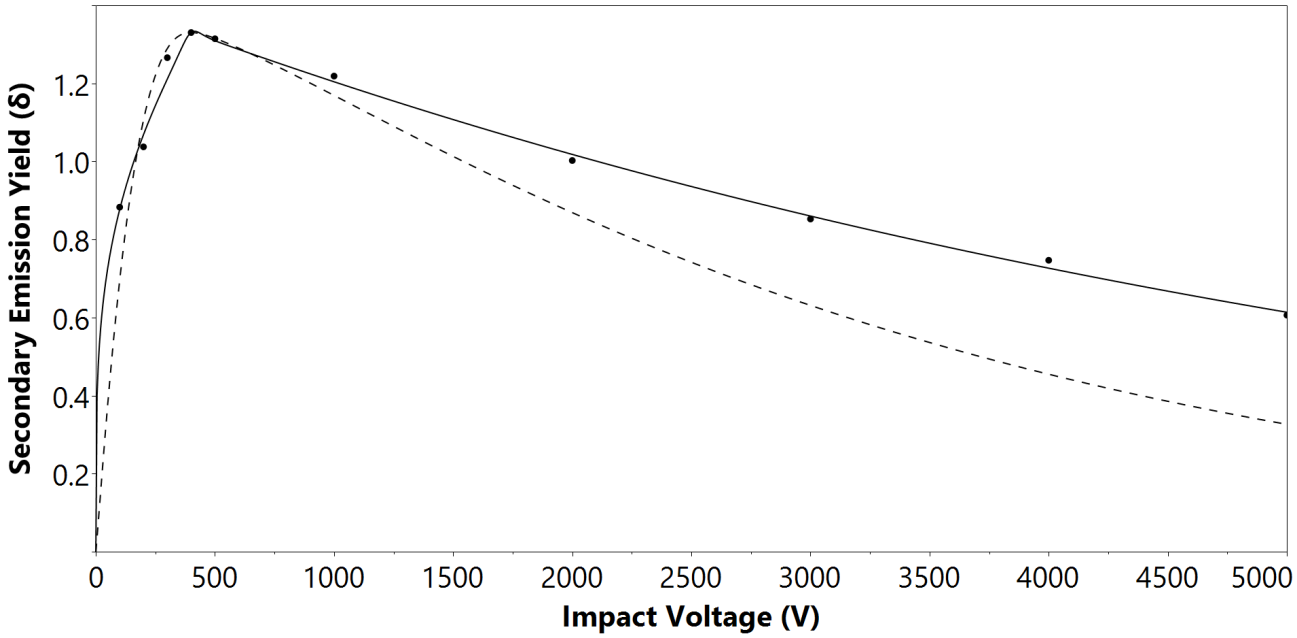

FIG. 6. Modified Vaughan fit (solid line, Eq. 5) versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on an unpolished Cu sample.

4.2 Materials with SEY data with maximum between 1.3 and 1.0

Figures 7 though 11 show data with SEY maxima between 1.3 and 1.0. Equation (1) can be applied on these SEY data sets, but its accuracy up to $3V_{max}$ is getting worse for lower values of the SEY maximum.

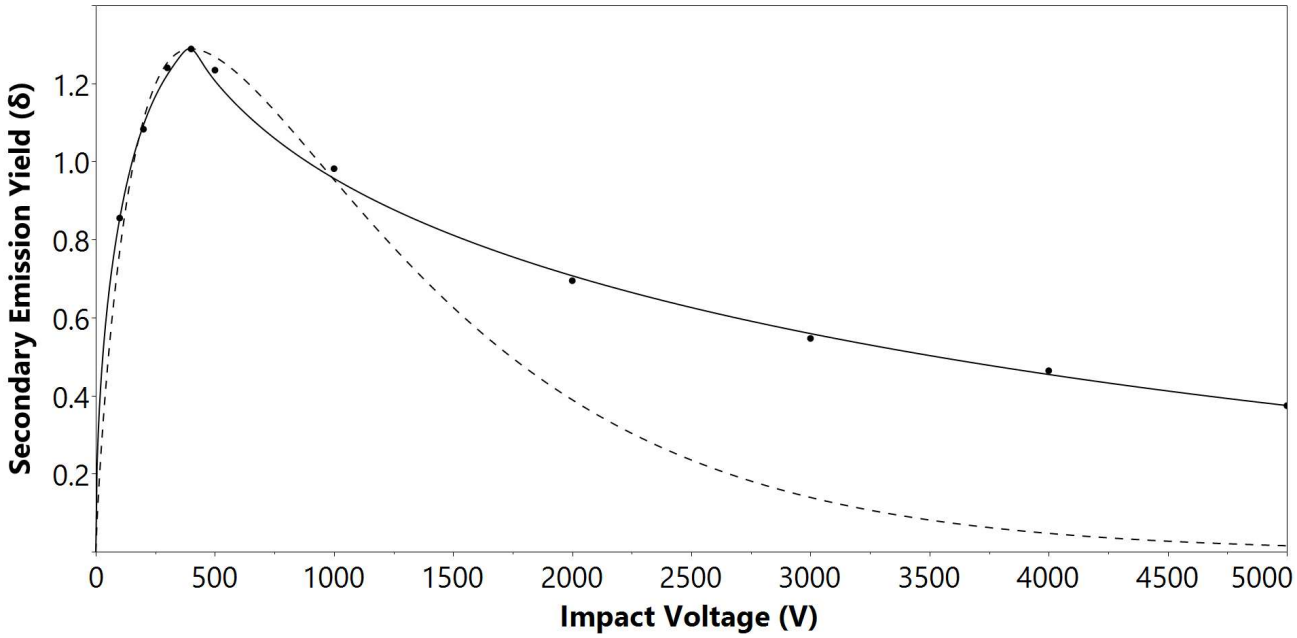

FIG. 7. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on a Cr sample.

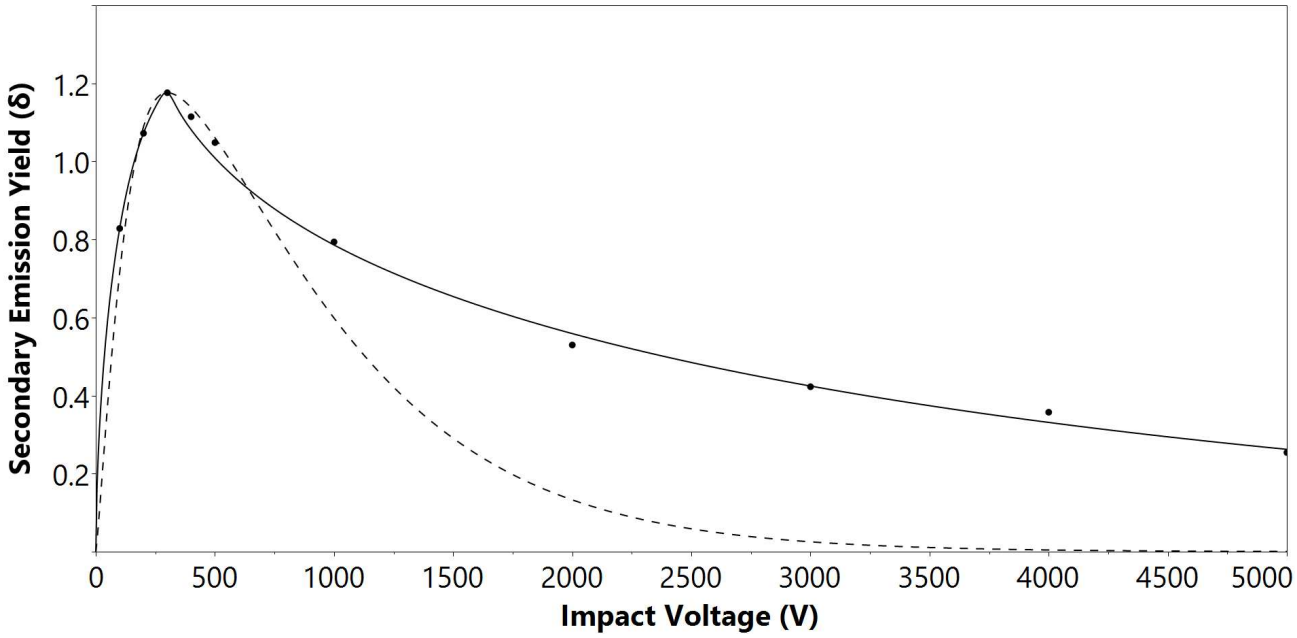

FIG. 8. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit, (dashed line, Eq. 1) to SEY data collected by us on a TiN sample.

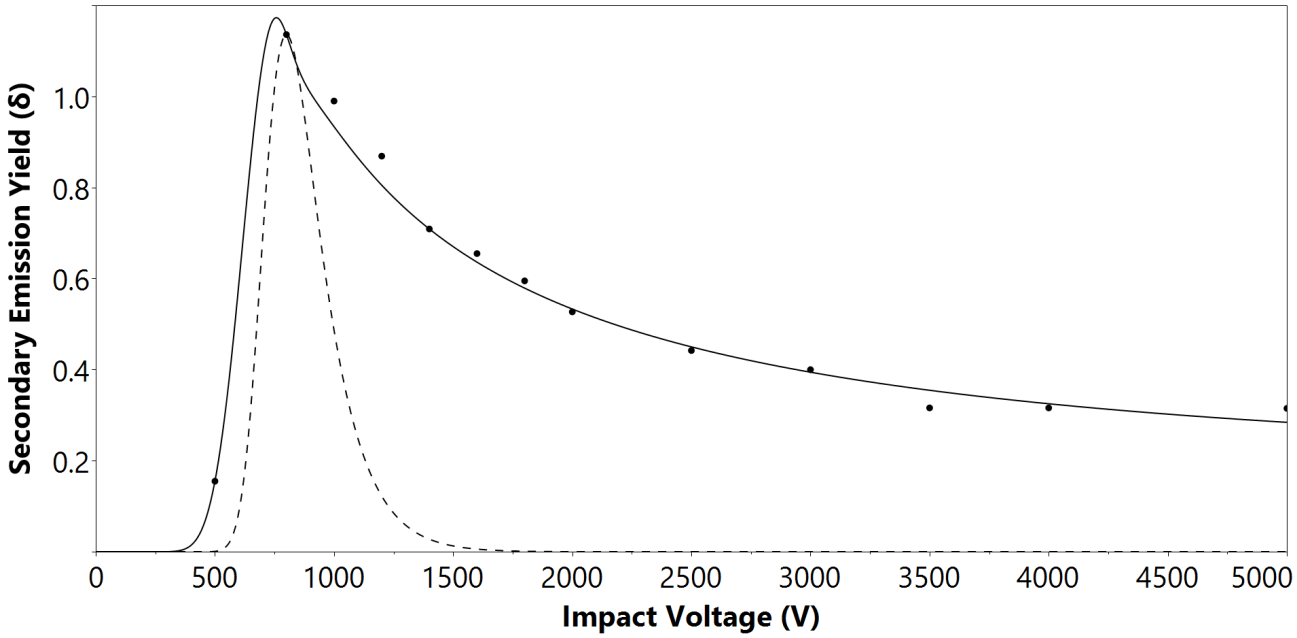

FIG. 9. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected on a C sample, as reported by Bongeler et al. [21].

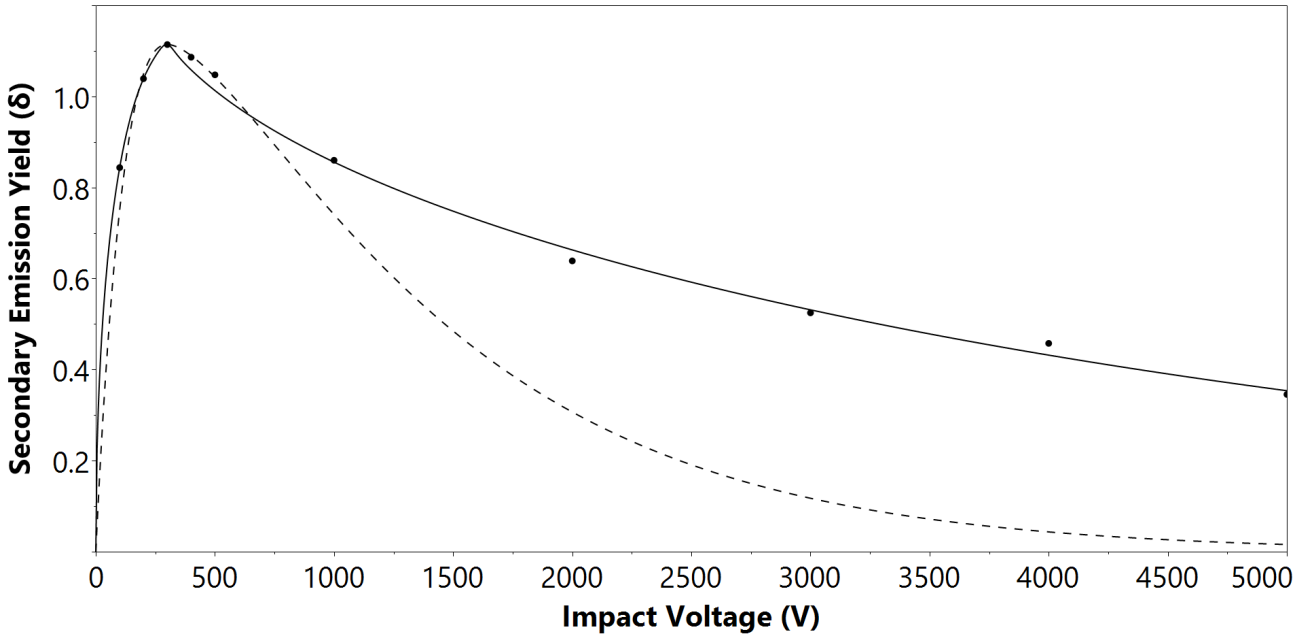

FIG. 10. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on a Mo sample.

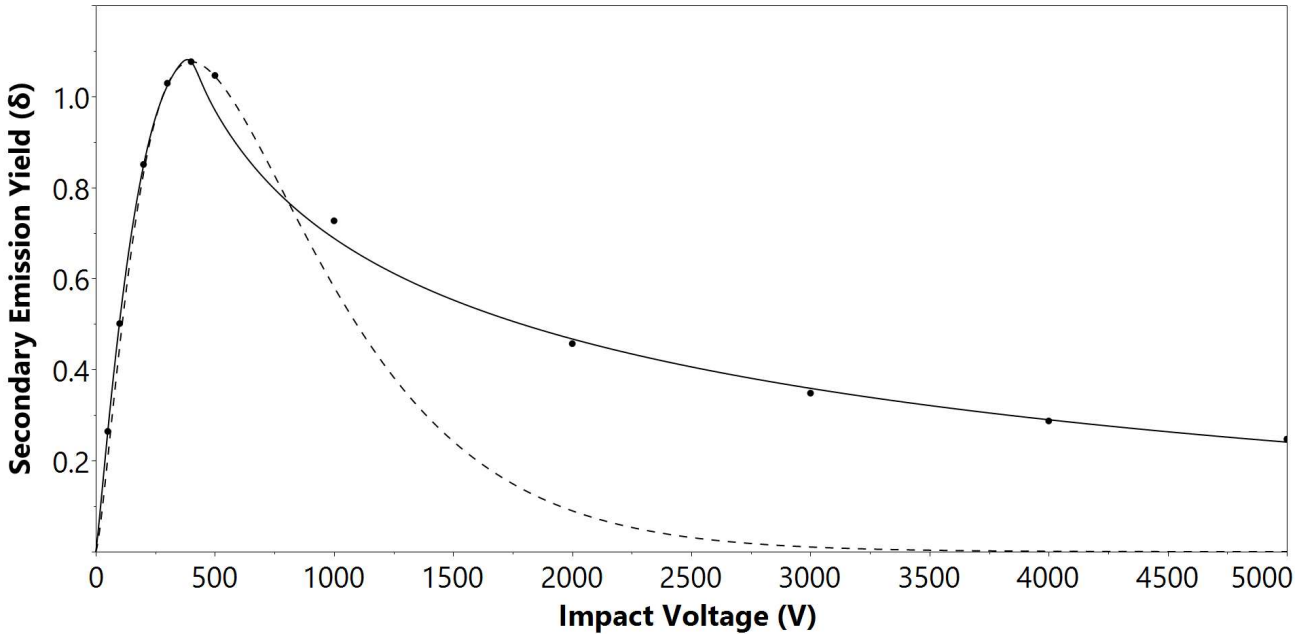

FIG. 11. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected on a Graphene-Ni sample, as reported by Joy [22].

4.3 Materials with SEY data with maximum below 1.0

Lastly, Figures 12 and 13 show data with SEY maxima below unity. Equation (1) is inapplicable for all these data sets, while Eq.(5) continues to provide good fits.

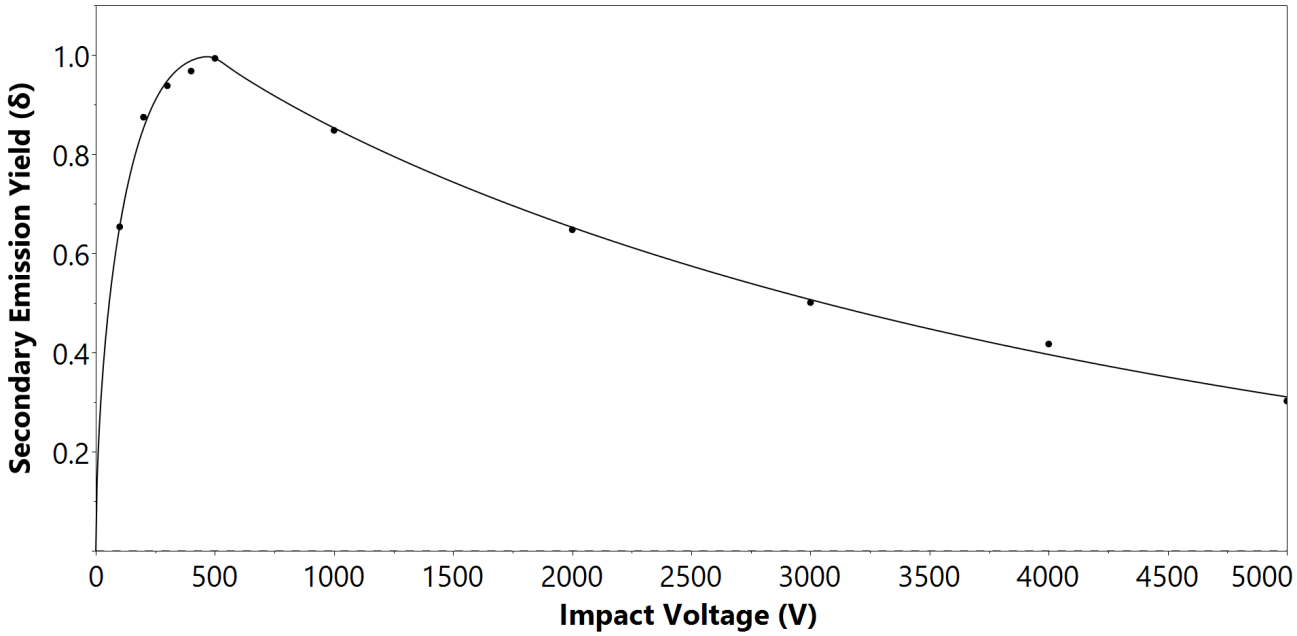

FIG. 12. Modified Vaughan fit (Eq. 5) for SEY data for Cu (polished). The original Vaughan fit is not shown here because there is no experimental data point with $\delta = 1$ above the location of the SEY maximum, which occurs exactly for δ =1.

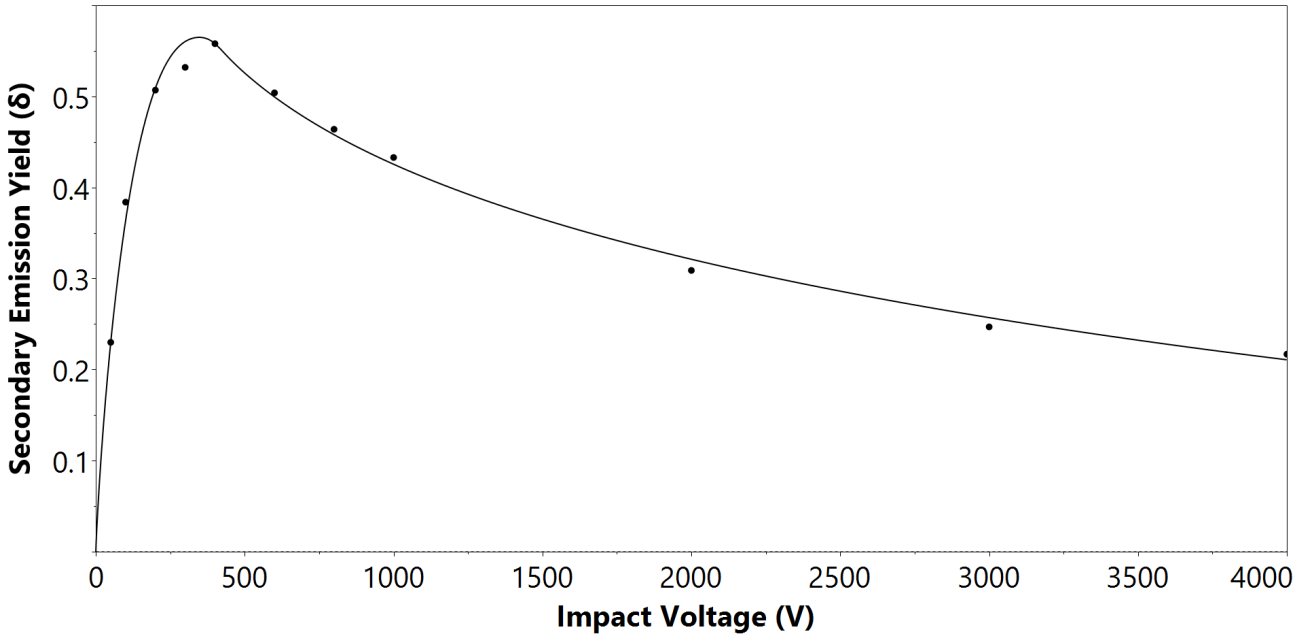

FIG. 13. Modified Vaughan fit (Eq. 5) for SEY data collected on a Ba sample, as reported by Joy [22]. The original Vaughan fit is not shown since the SEY maximum is below unity.

Tables I through III list the values of the five critical point coordinates, the values of the k fitting parameters, and the corresponding values of the $\Gamma_{\alpha,\beta}^{L,H}$ fitting parameters for each SEY data set analyzed in this work. A graphical user interface generating the optimal $\Gamma_{\alpha,\beta}^{L,H}$ fitting parameters for given SEY data is available at the following website [23].

TABLE I. Values of the five critical points for each SEY data set analyzed in this work. The impact votlage is in units of kV. Associated values for $\Gamma_{\alpha,\beta}^{L,H}$ can be found in Table III.

Material	δ_{max}	V_{max}	δ_{α}^{L}	V_{α}^{L}	δ_{β}^{L}	V_{β}^{L}	δ_{α}^{H}	V_{α}^{H}	δ_{β}^{H}	V_{β}^{H}
Au	1.63	1	0.844	0.119	1.29	0.356	1.43	2.61	1.2	4.54
Ni	1.58	0.4	0.82	0.104	1.22	0.243	0.777	2.87	0.475	4.78
Cu Unpolished	1.33	0.4	0.895	0.108	1.13	0.24	0.831	3.21	0.636	4.79
Cr	1.29	0.4	0.859	0.102	1.18	0.265	0.731	1.87	0.376	4.98
TiN	1.18	0.3	0.829	0.1	1.07	0.2	0.42	3.04	0.275	4.8
C	1.14	0.8	0.156	0.5	0.253	0.53	0.709	1.4	0.344	3.67
Mo	1.11	0.3	0.844	0.1	1.04	0.2	0.515	3.15	0.368	4.8
Graphene-Ni	1.08	0.4	0.275	0.0522	0.841	0.197	0.48	1.92	0.281	4.17
Cu Polished	0.993	0.5	0.654	0.1	0.803	0.168	0.682	1.83	0.327	4.78
Ba	0.558	0.4	0.23	0.0501	0.42	0.129	0.333	1.81	0.233	3.45

TABLE II. Values of the k fitting parameters calculated for each SEY data set analyzed this work.

Material	Original Vaughan		Modified Vaughan			
	k_1	k_2	k_1^L	k_2^L	k_1^H	k_2^H
Au	N/A	N/A	0.465	0.378	0.0272	0.0975
Ni	1.58	0.222	0.428	-0.106	-0.0563	0.0968
Cu Unpolished	1.09	0.118	0.255	-0.0854	0.0022	0.0678
Cr	0.837	0.478	0.48	0.337	-0.233	0.0562
TiN	1.21	0.543	0.575	0.422	-0.229	0.0546
C	91.1	5.42	25.8	27	-0.918	-0.0567
Mo	0.974	0.307	0.48	0.374	-0.118	0.052
Graphene-Ni	1.39	1.01	1.14	1.11	-0.429	0.036
Cu Polished	N/A	N/A	0.553	0.59	-0.0528	0.116
Ba	N/A	N/A	0.838	0.978	-0.223	0.0512

TABLE III. Values of the $\Gamma_{\alpha,\beta}^{L,H}$ fitting parameters for each SEY data set analyzed in this work.

Material	Γ_α^L	Γ_β^L	Γ_α^H	Γ_β^H
Au	0.04	0.58	0.58	0.099
Ni	0.016	0.54	0.3	0.035
Cu Unpolished	0.026	0.55	0.31	0.041
Cr	0.01	0.76	0.39	0.002
TiN	0.001	0.7	0.18	0.022
C	0.001	0.1	0.48	0.035
Mo	0.001	0.72	0.22	0.029
Graphene-Ni	0.013	0.71	0.28	0.04
Cu Polished	0.001	0.44	0.55	0.036
Ba	0.001	0.58	0.34	0.048

5 Conclusions

A new mathematical expression for SEY as a function of the impact voltage is proposed which is an extension of the formula first proposed by Vaughan [18] to fit SEY data up to a maximum impact voltage range of 5 kilovolts. As shown in section 4, the new analytical expression consistently gives better fits to SEY data compared to the original Vaughan expression, even

when the SEY maximum is only slightly larger than unity. The new expression also allows to fit SEY data when their maximum is below unity, a case for which the original Vaughan approach cannot be applied. The dynamic nature of the critical points used to provide an LMS fit to SEY data allows the technique to be successfully implemented on most SEY data sets, regardless of their SEY maximum, including a much better fit to the high impact voltage tail of the SEY plots. However, the original fit provided by Vaughan is typically very accurate for energies very close to the SEY maximum (i.e., within the range V_{max}±0.1 keV). In this range, the original Vaughan formula may provide slightly more accurate results than the new analytical expression in some cases such as Figures 5,8,10, and 11.

A more systematic approach among researchers should be followed by researchers measuring SEY data. For instance, since the maximum of SEY data occurs around a few hundred volts, a collection of SEY data should probably be done every 50V for the voltage range from the threshold value in the impact voltage up to about 1000V. For SEY data recorded between 1 and 5kV, because the SEY data typically fall smoothly as the impact voltage increases, SEY data could probably be taken every 250V. The SEY data taken by our group had more data points below 1kV to resolve the SEY max. We took only SEY data points every 1kV between 1kV and 5kV. In this high impact voltage regime, the SEY curve it typically very smooth. Considering the smoothness of the SEY curve above the maximum, this should not affect much the value of the parameter k2. More data points below the maximum could affect slightly the values of the k1 parameter reported here.

The new fitting technique could be of great use in various applications requiring accurate modeling of SEY data, including the design of photomultiplier tubes, scanning electron microscopes, plasma TV displays, cold-cathode amplifiers, and the collector of a klystron, among others.

Acknowledgments

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Figure Captions

FIG. 1. (Color online) Schematic representation of impact voltage dependence of SEY data. In Vaughan's approach, three critical points are used to fit SEY experimental data: the location of the SEY maximum and the two values of the impact voltage at which the SEY (delta) reaches unity. These two values are labeled v_1 and v_2 below and above the SEY maximum, respectively. The values of the impact voltage are normalized using Eq.(2). In these units, the SEY maximum occurs at v_{max}.

FIG. 2. (Color online) Location of the five critical points selected to perform a fit to a set of SEY experimental data. The improved Vaughan fit requires knowledge of 5 critical points including the location of the SEY maximum, two SEY values below the SEY maximum, and two SEY values above the SEY maximum (points 1 through 5). The superscripts L and H correspond to data below (V_α^L, V_β^L) and above (V_α^H, V_β^H) the location of the SEY maximum, V_{max}, respectively.

FIG. 3. (Color online) Diagram of experimental setup to record SEY data of various materials.

FIG. 4. Modified Vaughan fit (Eq. 5) to SEY data collected by us on a Au sample. The original Vaughan fit is not shown since no experimental data points for which $\delta = 1$ on the high impact voltage side was measured.

FIG. 5. Modified Vaughan fit (solid line, Eq. 5) versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on a Ni sample.

FIG. 6. Modified Vaughan fit (solid line, Eq. 5) versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on an unpolished Cu sample.

FIG. 7. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on a Cr sample.

FIG. 8. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit, (dashed line, Eq. 1) to SEY data collected by us on a TiN sample.

FIG. 9. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected on a C sample, as reported by Bongeler et al. [21].

FIG. 10. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected by us on a Mo sample.

FIG. 11. Modified Vaughan fit (solid line, Eq. 5), versus original Vaughan fit (dashed line, Eq. 1) to SEY data collected on a Graphene-Ni sample, as reported by Joy [22].

FIG. 12. Modified Vaughan fit (Eq. 5) for SEY data for Cu (polished). The original Vaughan fit is not shown here because there is no experimental data point with $\delta = 1$ above the location of the SEY maximum, which occurs exactly for δ =1.

FIG. 13. Modified Vaughan fit (Eq. 5) for SEY data collected on a Ba sample, as reported by Joy [22]. The original Vaughan fit is not shown since the SEY maximum is below unity.