Electron Yield Decay Curves for Analysis of Sample Charging and Neutralization

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Introduction

Excess charge on a material will affect the electron yield of the material. Electron yield is an attribute of materials which describe how the material behaves when irradiated with electrons. It is the ratio of the number of electrons going into the material over the number of electrons leaving the material. Understanding how a sample charges is important in both how it affects the electron yield and how it can be neutralized.

Electron yield measurements are made in a vacuum chamber, by irradiating a material with an electron beam. Incident electrons interact with the material through inelastic and elastic collisions. The incident electrons will either end up deposited within the material or leave the surface of the material as backscattered electrons. These interactions, which deposit energy in the material, have a chance to produce secondary electrons within the material. These secondaries then have a chance to either escape from the surface of the material or become reabsorbed within the material. All the escaping electrons, both secondary and backscatter, are collected and measured. The charge on the sample is also measured. Using these measurements, the total electron yield σ_{tot} can be calculated as:

$$\sigma_{tot} = \frac{Q_{collectors}}{Qsample + Qcollectors} = \frac{Q_{se} + Q_{BSE}}{Q_{Inc}} \quad (1)$$

where $Q_{collectors}$ is the sum of the charge collected in all the elements in our electron detector: stage, inner grid, bias grid, and collector. Q_{sample} is the net charge collected in the sample. Another way to look at the formula is a physical definition of what is collected. The collectors collect everything leaving the sample which are the secondary electrons Q_{se} and the backscatter electrons Q_{BSE}. All the charge together sums up to the incident charge Q_{inc}. In other words, the total electron yield is the electrons out over the electrons in. This ratio is dependent on the energy of the incident electron beam.

There are two other types of electron yield which should be addressed. Backscatter yield η is defined as

$$\eta = \frac{Q_{BSE}}{Q_{Inc}} \quad (2)$$

and secondary electron yield δ is defined as

$$\delta = \frac{Q_{se}}{Q_{inc}} \quad (3)$$

Secondary electrons and backscatter electrons are collected together. There is no way of distinguishing them. However, they can be distinguished by their energy distribution. Most secondary electrons are low energy defined by an operational convention to be less than 50 eV. Backscatter energies are usually closer to the incident beam energy, and by convention are considered anything above 50 eV. By making this distinction backscatter yield η can be measured by filtering out the secondary electrons. This is achieved by applying a -50 V bias between the sample and the collector.

Although it is possible using emission spectra to calculate the secondary electron yield, it is easier to use this relationship to calculate the secondary electron yield

$$\sigma_{tot} - \eta = \delta \quad (4)$$

$$or$$

$$\frac{Q_{se}+Q_B}{Q_{Inc}} - \frac{Q_B}{Q_{Inc}} = \frac{Q_{se}}{Q_{Inc}} \quad (5)$$

Subtracting the backscatter yield from the total yield gives the secondary electron yield.

Electron yield measurements for conductors are a straightforward process as described above. Charge deposited in the sample flows through the sample to ground and no stray electric fields are ever produced. Insulators or otherwise poor conductors are much more difficult to take accurate electron yield data on. Charge deposited into the material stays there. Q_{sample}, the current from the rear sample electrode to ground, is a displacement charge for insulators rather than the direct current measured for conductors. As the sample begins to accumulate charge, it produces electric fields which affect the incident electrons, the backscatter electrons, and the secondary electrons. How the material charges up will depend on the electron yield of the material and the incident beam energy, as well as the material conductivity.

For insulators there are two charging regimes, positive and negative. These charging regimes can be defined using the crossover energies E_1 and E_2. The crossover energies are defined as the incident beam energy which results in a total yield of one, that is the same number of electrons out as electrons in and hence no net further charging. The positive charging regime is between the crossovers E_1 and E_2. The negative charging regimes are below E_1 and above E_2.

Both negative and positive charge are created by the incident electron beam. Negative charge is caused by electrons being deposited into a material from the incident electrons. Positive charge is created within a material when a secondary electron escapes the material leaving behind a hole. Insulators will charge up negatively or positively depending on whether there are more holes being generated or more electrons being deposited. This means an insulator will charge positively between the crossover energies where the yield is greater than one and negatively outside the crossover energies where the yield is less than one.

Positive Charging

Positive charging occurs in insulators when the yield is greater than one or between the crossover energies. The effects of the charging on the electron yield can be characterized using electron yield decay curves. Yield decay is the measurement of yield changes in response to incremental sample charging. Measurements are taken consecutively, and no attempts are made to neutralize the charge between pulses. This allows the sample to charge incrementally with each pulse.

For Kapton HN ™ (Polyimide) a yield decay curve was produced at 200 eV. The incident beam was characterized by placing the beam over a Faraday cup after measurements where completed. The beam was roughly 4.5 mm in diameter and contained about 117 fC per pulse. Assuming relatively consistent beam throughout the measurement prosses the accumulated incident charge and deposited charge can be calculated.

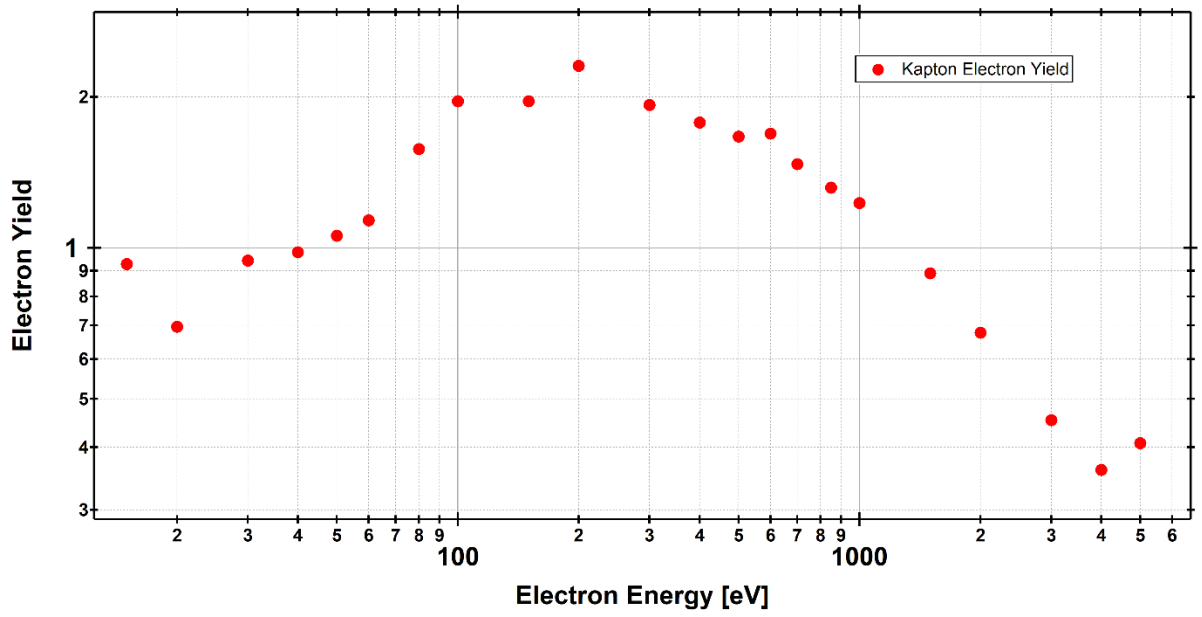

Figure 1 Total electron yield curve of Kapton HN ™

The total incident charge is simply the sum of the charge per pulse over the number of pulses Figure 2 (a). The amount of charge deposited per pulse, as show in Figure 2 (b), needs to be calculated. Deposited charge per pulse can be expressed as

$$Q_{dep} = Q_{inc} - (Q_B + Q_{se}) \quad (6)$$

Combining this with the equation for total electron yield (Eq. 1) the net deposited charge is

$$Q_{dep} = Q_{inc}(1 - \sigma_{tot}) \quad (7)$$

This equation can also be written as

$$Q_{dep} = N_{inc}(\sigma_{tot} - 1) \quad (8)$$

where N_{inc} is the number of incident electrons. This equation needs to be summed over the number of pulses to get the total accumulated charge. Figure 2 (b) is the accumulated net deposited charge versus the number of pulses. Unlike the incident charge versus pulse graph, this graph is nonlinear. As the yield σ_{tot} decreases towards one, the deposited charge Q_{dep} decreases towards zero. Eventually no more charge can be deposited, as the yield reaches unity and charge has reached equilibrium. Two yield decay curves are plotted for Kapton HN ™ at a beam energy of 200 eV, as seen in Figure 2 (c) and Figure 2 (d).

Figure 2 (c) is the electron yield versus the incident charge. This decay curve shows the change in yield per pulse is approximately exponential. After only a few pulses the sample can charge enough to reduce the yield a large amount. This is a good example of why taking accurate yield measurements of insulators is difficult.

Figure 2 (d) is the electron yield versus deposited charge. This graph shows that there is a near linear relationship between the yield decay and the deposited charge. In both yield decay graphs the yield decays towards one. This point of equilibrium can be explained by the primary mechanism causing the yield to decay, the reattraction of secondary electrons.

Figure 3 is a typical secondary electron emission spectra. Most of the secondary electron energies are around 4 eV. Although every material's emission spectra are different the peak probable energies are typically between 1eV and 5eV. The sample only needs to charge a few volts positive to reabsorb most of the escaping secondary electrons. As the sample charges it begins to reattract more and more electrons until equilibrium is achieved. This happens when no more net charge is being deposited per pulse. The positively charged surface attracts just enough secondaries back to the surface to keep the deposited

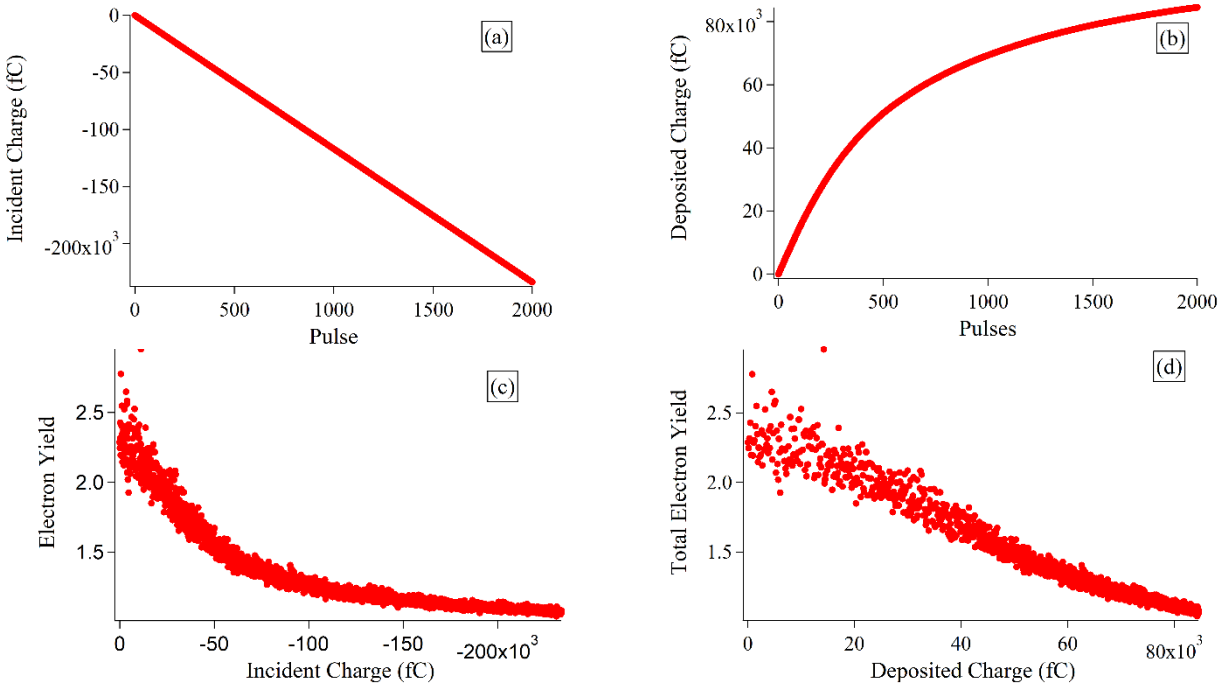

Figure 2 (a) Incident charge vs number of pulses. (b) Deposited charge vs number of pulses. (c) Electron yield vs incident charge. (d) Electron yield vs deposited charge.

charge the same, resulting in a total electron yield of one.

Positive sample charging has little effect on backscatter yield. Backscatter electrons are by convention defined as having an energy greater than 50 eV. At maximum positive charging, the surface potential only ever reaches a few volts positive. This is much too low to reattract the higher energy backscatter electrons, resulting in almost no change in the backscatter yield. Small positive charge also has minimal effect on the landing energy of the incident electrons.

The secondary electron yield is reduced in the same way as the total electron yield. The equilibrium value for the secondary electron yield occurs at one minus the backscatter yield,

$$1 - \eta = \delta. \tag{9}$$

Negative Charging

Negative charging occurs in insulators in the negative charging regime at incident beam energies below the first crossover or above the second crossover. A yield decay curve for Kapton HN ™ was produced at 5000 eV, well above E_2.

As before, the incident beam was characterized by placing the beam over a Faraday cup after measurements where completed. The beam was roughly 0.7 mm in diameter and contained about 3000 fC per pulse. Assuming relatively consistent beam throughout the measurement prosses, the accumulated incident charge and deposited charge can be calculated.

As before, the incident charge per pulse is estimated to be a constant value as measured in the Faraday cup. The accumulated incident charge is simply the sum of the charge per pulse over the number of pulses. The deposited accumulated charge can be calculated the same way as before (Eq 8).

The yield decays approximately exponentially towards a yield below one (Figure 3). In the case of negative charging the primary mechanism for reducing the yield is the effect of the negative charge on the incident beam. As the negative charge builds up it begins to repel the incident electrons lowering the landing energy. Reducing the landing energy increase the yield increases.

In an ideal insulator the sample would continue to charge until the landing energy equals the second crossover energy.

$$E_L(Q_{max}) = E_2 \tag{10}$$

This is because the electron yield at crossover energy is equal to one. The number of electrons coming in and out of the material per pulse are equal, so no more net charge is being accumulated.

Real world insulators may not decay to a yield of one. There are a few factors which can affect

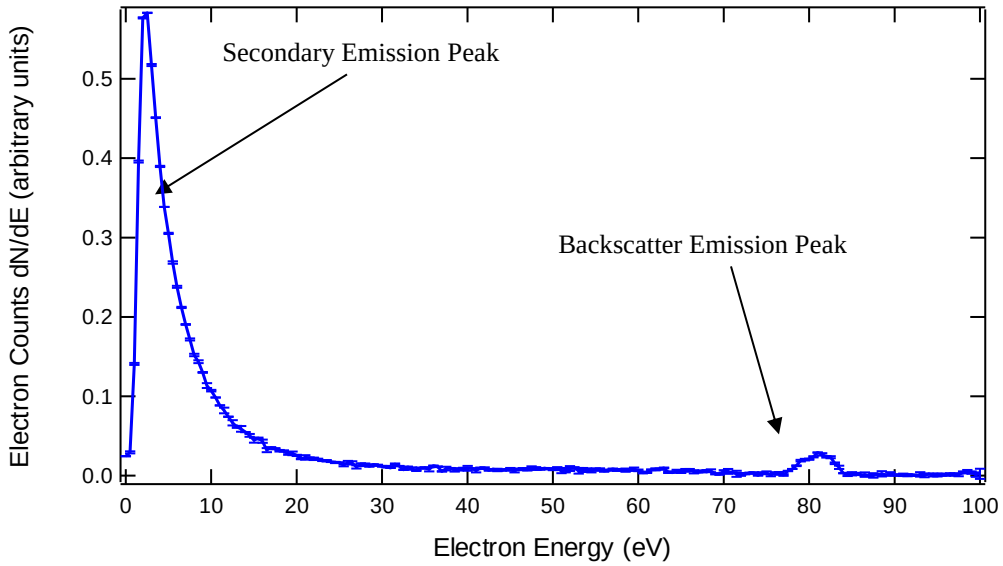

FIG. 3 Electron emission spectra from polycrystalline Au.

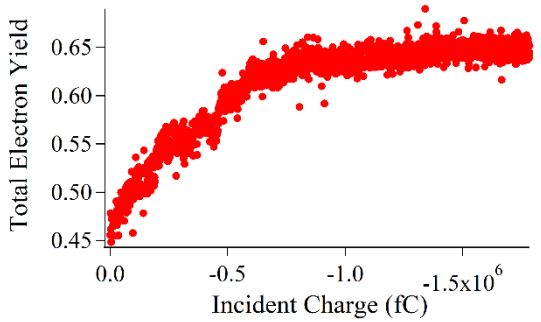

Figure 4 Electron yield vs incident charge

the equilibrium surface voltage and yield achieved in insulators. All insulators have a finite resistance and can have a leakage current through the sample in addition to the displacement current caused by the accumulation of internal charge. This means equilibrium occurs when the leakage current equals the rate of charge being deposited into the sample. Changing the rate of deposited charge can change the equilibrium value for the yield. Other factors such as contamination, radiation induced conductivity, and photoconductivity can all increase the conductivity of the material, and thereby affect the equilibrium yield in similar ways.

In an ideal insulator the maximum surface potential an insulator can obtain is the difference between the incident beam energy E_o and the second crossover energy E_2.

$$V_{max} = \frac{E_o - E_2}{q_e} \tag{11}$$

where q_e is the charge on an electron. This means insulators can achieve very large negative charge. Enough charge can build to cause electrostatic discharge in the material. The criterion for breakdown is then

$$V_{max} > V_{esd} \tag{12}$$

or

$$\frac{E_o - E_2}{q_e} > \frac{F_{esd}}{d_s} \tag{13}$$

where F_{esd} and V_{esd} are the breakdown field strength and breakdown voltage and d_s is the sample thickness.

Backscatter yields are also affected by negative charging. By convention secondary electrons are considered to have energies below 50 eV. As a material begins to charge up negatively it begins to accelerate the secondary electrons escaping the surface. This has the effect of increasing secondary kinetic energies up by q_eV_s so that they are higher than 50 eV, where they are then counted by the system as backscatter electrons. This artificially raises the measured backscattered yield. This is commonly seen in insulators just above the second crossover. This effect can be seen in the backscatter yield of Kapton HN ™ in Figure 5 just above 1000 eV the backscatter yield is higher than is should be.

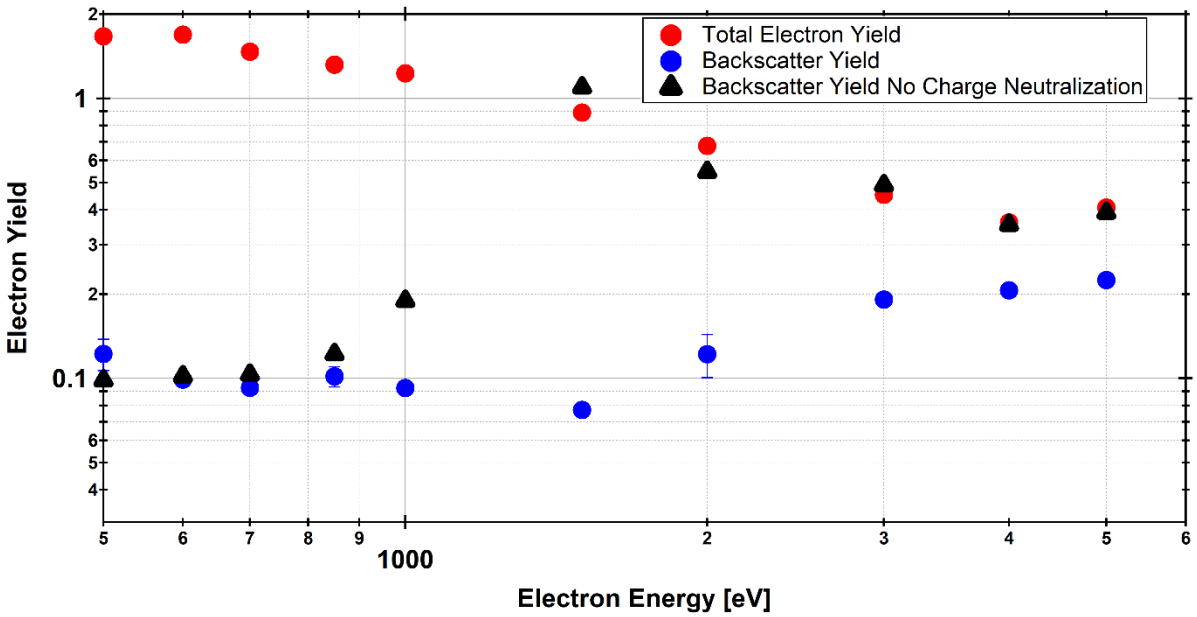

Figure 5. Total electron yield (red), backscatter yield (blue), and backscatter yield no charge neutralization (black).

When charged to at least -50 V all the secondaries will gain enough energy to be counted as backscatter electrons.

$$Q_B \rightarrow Q_B + Q_{se} \quad (14)$$

When this happens the measured total electron yield and the backscatter electron yield will be equal. This can be seen in the black data set in Figure 5. This data set was not neutralized between pulses. Above E_2 the black data jumps up and is in good agreement with the total electron yield (red data).

Secondary electron yield is reduced by negative charging because of our definition of secondary electrons. As negative surface voltage is increased, a portion of secondary electrons gain enough energy to have emission energies greater than 50 eV and are counted as backscatter electrons. At -50 V all secondary electrons are counted as backscatter electrons and the secondary electron yield goes to zero. Physically the secondary electron yield is not being reduced. However, since a convention is needed to distinguish the secondary from backscatter electrons the yield is reduced by the secondaries being converted to backscatter electrons in the calculations.

Charge Neutralization

Ideally a sample needs to be completely charge neutral to obtain its intrinsic electron yield. Contamination, charging, surface roughening and other modifications can all influence the yield of a material. Intrinsic yield is the yield of an unmodified material. Charge can be removed from a sample in a few ways. Positive charge can be removed by flooding the sample with low energy electrons. Negative charge can be removed with UV light. heat can help to neutralize a sample by increasing its conductivity and allowing the excess charge to migrate to ground or for electrons and holes to recombine. Each of these methods have their limitation.

Low energy electrons are extremely effective at removing positive surface charge. Figure 6 shows how effective they can be. This graph has almost the exact experimental setup as the yield decay curve taken above at 200 eV (Figure 2(c)). However, in this case a low energy (6 eV) electron gun flooded the Kapton HN ™ for one second between pulses, neutralizing the positive charge on the surface. Over the 500 pulses the yield does not decay. The limitation of this method is the electrons can only directly neutralize surface charge, limited by the range of the

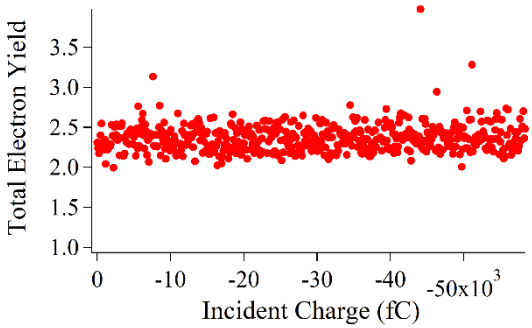

Figure 6. Kapton HN ™ Yield decay graph at 200eV vs incident charge. Charge was neutralized with electron flood gun between pulses.

electrons. They are unable to neutralize deeper positive charge, because of their low energy. Electrons deposited near the surface by the flood gun can create a dipole layer with surface charge density sufficient to match that of the embedded charge density (as corrected for the permittivity of the dielectric material). this results in a measured surface voltage of zero above the grounded rear electrode on the sample. However, the dipole layer can still affect the electron yield to some extent.

UV light is effective at removing excess electrons from the surface of the material through the photoelectric effect. The effect of the UV light can be seen by comparing the blue backscatter data with the black backscatter data above 1000 eV in Figure 5. The blue data was neutralized with a UV LED between measurements. The black data was not neutralized between measurements. There is still some charging in the blue data as it looks slightly elevated, however it is clearly not nearly as charged as the black data set. The black data set appears to have charged to a surface potential of -50 V or higher. Since the blue data set is lower than the black data its surface potential must be less than -50 V. However, even a small residual negative bias can still excite electrons in the higher energy tail of the secondary energy distribution (see Figure 3) to energies above -50eV. The UV light can only neutralize negative surface charge. At increasingly higher beam energies charge is deposited deeper within the sample, decreasing the amount of charge able to be removed by the UV light.

Deep charge can be neutralized by heating the sample. However, there is no quick way to remove these deep electrons between measurements. Depending on the material, it can take a long time for the charge to leave the sample. Even if the material

quickly dissipates charge, the material will need time to cool off before more measurements can be made.

Conclusion

The electron yield of insulator is greatly influenced by the accumulated charge. Generally charging effects can be spotted in data if it moves the yield towards one. Either because positive charging is reattracting secondary electrons to the material lowering the yield, or negative charging is reducing the landing energy and increasing the yield. Charge neutralization methods can be employed to increase the accuracy of the electron yield by removing the excess charge.