Surface Modification Influences on Electron Yield

Matthew Robertson and JR Dennison

Materials Physics Group
Utah State University

Abstract: Electron yield is sensitive to surface modifications such as charging effects, surface roughness, and contamination. Understanding these different surface modifications and how they influence electron yield is important to understand which measurements will accurately describe the yield of a material in its real-world environment.

Introduction

The primary surface modifications discussed are charging, roughness, and contamination layer structures. These surface modifications are common and often unavoidable in real-world applications. A pristine material can have electron yield values that are significantly different than material with surface modifications. The objective of this paper is to explain why surface modifications should be taken into account when considering electron yield measurements.

Electron yield is defined as the ratio of electrons out over electrons in. It is measured by irradiating a sample with an electron beam and measuring the ratio of secondary electrons emitted from within the material to incident electrons from an electron gun. It a function of beam energy. Electron yield is used in understanding, modeling and mitigating spacecraft charging. It is also used in scanning electron microscopes[5], particle accelerators, plasma TV displays[6], phototubes, electron multipliers, microwave multipactors[7], ion thrusters[8], and high-voltage insulators.

Each material has its own unique electron yield which is determined by its chemical composition; however, there are many other factors that can change the yield for any material. Figure 1 shows various studies on the yield of copper taken over the years. The difference in measurements can be attributed to different surface modifications. Charging effects, surface morphology, contamination, layered structures, temperature, and irradiation conditions can all change the electron yield of a material.

Charging

When an insulator is subjected to electron irradiation it can charge. Charging is a common occurrence and understanding the behavior of insulators under these conditions is of interest in many fields of science and technology from spacecraft charging to radiobiology[9].

Charging also occurs in a scanning electron microscopy (SEM) and many other forms of microanalytical techniques[10]. Charging effects cause insulators undergoing microanalysis to produce images that are distorted. The distortions are caused by the electric field produced by the stored charge and are correlated with the magnitude of the electrical potential induced in the insulator surface[9]. The yield of the secondary electrons emitted from the sample is important for interpretation of the image[3].

Charging also occurs for spacecraft materials, which can result from operating an ion thruster or when drifting through plasma in space. This charge can build up and cause damage to the spacecraft. Understanding the electron yield of a material is important for engineers to select appropriate

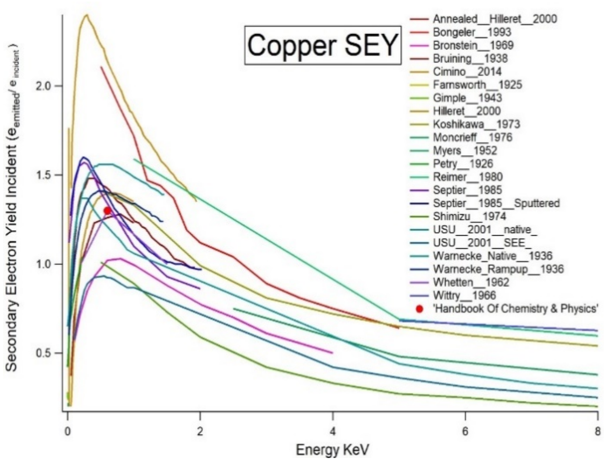


Figure 1. Measurements of electron yield curves taken from different groups over the years[2].

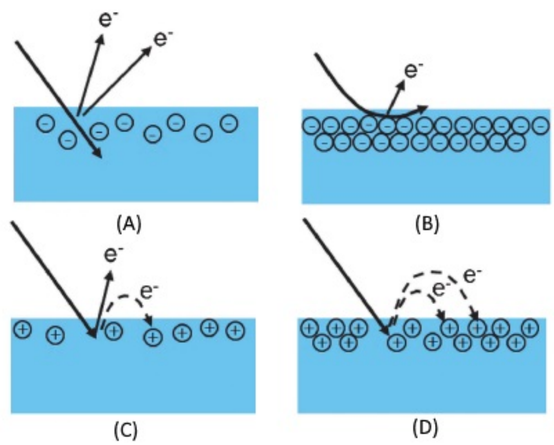


Figure 2. Illustrations of samples undergoing electron beam irradiation[3]. (A) negative charge repeling electrons from the surface. (B) a strong negative surface charge on sample deflecting incoming beam. (C) positivly charged sample reattracting secondary electrons. (D) Large positive surface charge preventing secondaries from escaping.

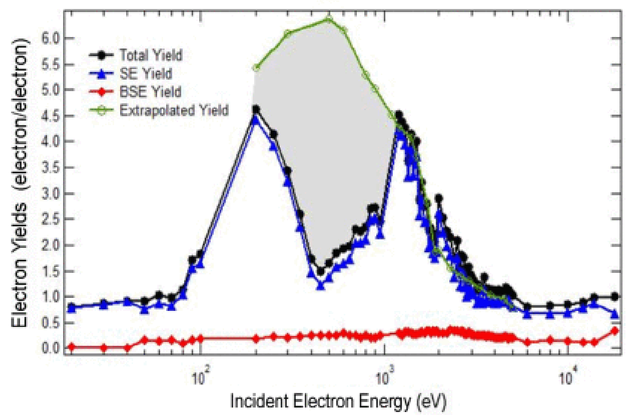


Figure 3. Measured electron-induced yield curve from 1-mm-thick 99.9% pure polycrystalline aluminum oxide. The depression in yield for 200 eV≤E_o≤1000 eV, which produces the observed dual peaks, is due to the positive surface charging. The upper curve through the open circles is the predicted yield.[4]

materials for their spacecraft, to minimize damage from such spacecraft charging.

Irradiating a sample with an electron beam is the method used to measure electron yield of a sample. This can cause the sample to charge, influencing the results. If the material is charged negatively it can cause electrons to be propelled off the surface[3]. Alternatively, if a large negative charge builds up on the surface it can deflect incoming electrons and reduce the yield. If charged positively the sample begins to reattract the emitted electrons. If charged up enough secondary electrons will be unable to escape from the surface (see Figure 2).

Electron yield measurements are done by irradiating a sample with an electron beam. In the similar way that charge build up in a sample can be problematic in a SEM, it can change the yield measurements of a material. Figure 3 is an example of the electron yield measurments of a charged sample. In Figure 3 the valley between the two peaks is caused by the sample charging up positvely. Under normal conditions a pristine material will typically have only one peak. The intrinsic yield, or the yield the material would have if it did not charge up, is extropolated and displayed in green in Figure 3. Charging effects move the yield of a material towards one. When an insulating material's electron yield is greater then one it charges positively. For each incident electron that strikes the surface more electrons leave the material then enter it. Leaving behind a positively charged surface. Eventually the positive charge will start to reattract the lost electrons As seen in Figure 2 (D). This will lower the ratio of escaping electrons to incident electrons, lowering the yield towards one. In the case the electron yield of a material is below one. The an insulating material has more incident electrons embedding in the material then escaping the material. causing a negative charge build up. The negative electric field slows down the incident beam lowering its landing energy. Lowering the number of electrons entering into the material raising the electron yield towards one. The relatively flat portions of the in Figure 3 at the beginning and end of the graph are an example of negative charging. Figure 2 (B) illustrates the negative charge build up happening in then ends of the graph in Figure 3. The surface potentials resulting from the accumulated charge are reducing the incident landing energy[4]. This causes fewer electrons to be emitted lowering the yield.

It is difficult to measure the intrinsic yield of an insulator, but it can be done by neuturalizing the accumulated charge on sample before each measurement is taken. To get an acurate measurment of instrinsic electron yield, a sample should be completely neutral to avoid having incident or secondary electrons influenced by electric fields from a charged sample. Lowering the current and using shorter beam pulses helps to reduce charge build up during a mearument.

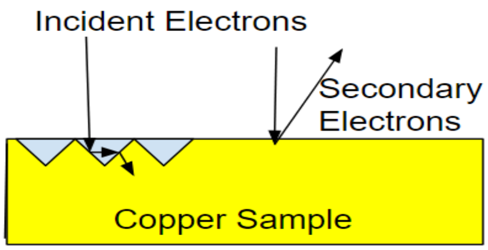


Figure 4. Illustration of incident electrons on a rough surface and a flat surface.

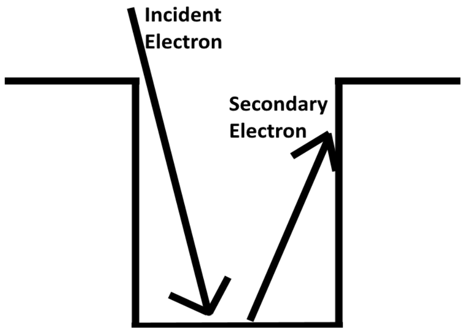


Figure 5. Illustration of an incident electron producing a secondary electron in a hole.

In real-world applications it is not always possible to neutralize a material or prevent it from acumulating charge. In situations or environments where charging is inevitable, electron yield models based on acumulative charge[4] may provide more acurate results.

Suface Morphology

When an incident electron is incident on the surface of a smooth flat material it will either reflect back off the surface or will produce secondary electrons (see figure 4). The secondary electron can travel from its point of generation off in any direction. In both cases there is a probability the electron will travel away from the material.

Surface roughness of a material decreases the chance an electron will escape. Whether the incident electron reflects off the surface or generates secondaries. There is a lesser chance the electron will escape from the surface than if it were flat. Figure 5 shows an extreme example of a secondary electron produced at the bottom of a hole. As can be seen in the illustration it is harder for the secondary to escape the material without encountering another surface. This helps to explain why rough surfaces are better at capturing electrons than smooth flat sufaces[11].

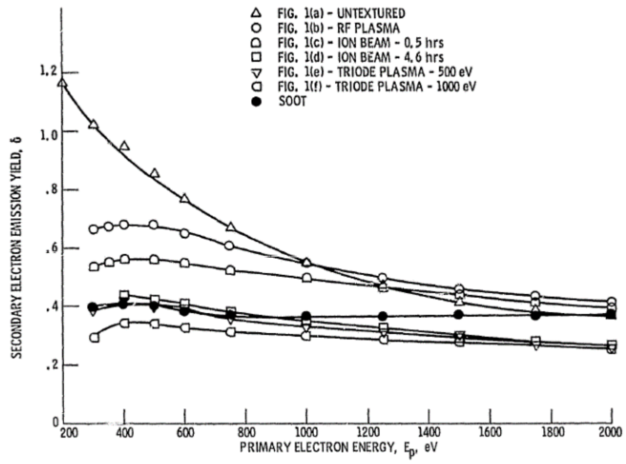


Figure 6 Effects of surface roughness on the electron yield of pyrolytic graphite. smooth Pyrolytic Graphite has the greatest maximum yield, it is shown on the graph with triangles. Apart from the line with solid black all the other lines are pyrolytic graphite that had undergone a sputtering treatment to roughen the surface. All the roughened surfaces have lower max yield then the smooth surface.[12]

Surfaces roughness can be changed by polishing a material. Polishing typically affects rouhness on a larger scale, anything larger than 0.1 micrometer. Roughness can also be changed on a much smaller scale with sputtering techniques. These techniques change the surface on a scale smaller then 0.01 mircrometers. How well roughness affects electron yield suppression is dependent on the aspect ratio of the holes. A shallow wide hole is nearly as easy to escape as a flat surface. Where as a deep narrow hole would be nearly impossible to escape. The aspect ratio and shape of the surface rouhness all play a part in yield supression.

In a study using Pyrolytic Graphite they used various sputtering techniques and settings to roughen the surface and lower the yield[12] (See Figure 6). At max yield the change from smooth to roughened surface was as great as nearly 70%.

Contamination and Layer Structures

The formation of the contaminate layer structure will depend on the material and its environment[13]. Any surface exposed to air will potentially run the risk of growing a contamination layer. The most common contaminations are carbon and oxygen[14] (see figure 7). These contamination layers are usually only a few nanometers thick.

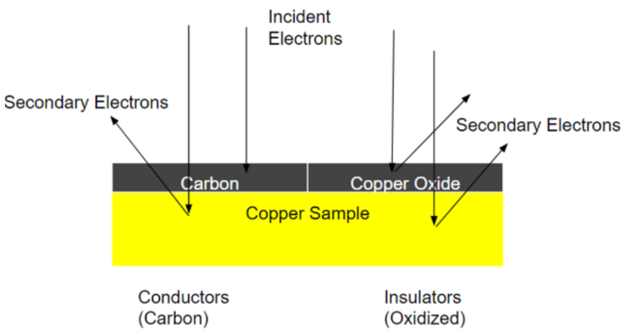


Figure 7. Illustration of contamination layers on copper.

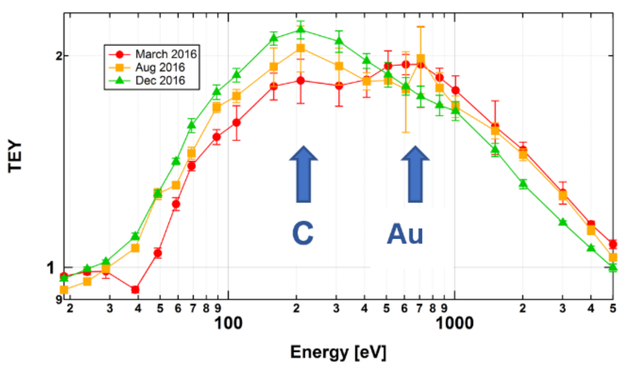


Figure 8 Electron yield measurements of a gold substrate with a carbon contaminate layer. This bilayer composite is interesting because both the carbon and gold peaks are visible in the yield curve.

Even thin layers can have a huge impact[15] on the electron yield of a material. This is because most electron emissions originate near the surface of a material especially for low energy incident electrons. This is explained in part by the depth of penetration of the incident electron. At low energies electrons do not penetrate very deeply, this causes them to primarily interact with the surface. At higher energies incident electrons have two opportunities to excite secondary electrons from the surface. High energy electrons can produce secondary electrons as they pass through the surface layer of the material, and again as they are reflected from deeper within the material and exit through the layer. This results in the electron yield to be largely influenced by the surface layer, especially at low incident electron energies.

Figure 8 shows a gold sample that became contaminated with a carbon layer. The graph has three different electron yield curves each taken a few months apart. The earliest measurements of electron yield are the red line. Two peaks can be seen clearly in this first data set. A small carbon peak and then the

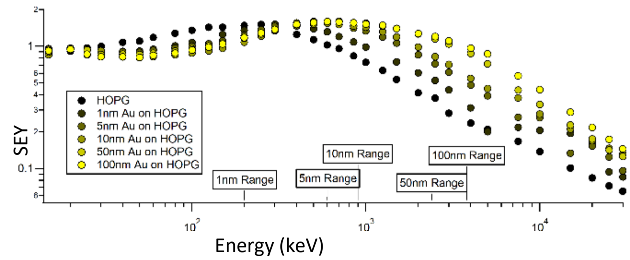


Figure 9. Layers of graphitic carbon with thicknesses ranging from 0.5nm to 500 nm on top of gold.[1]

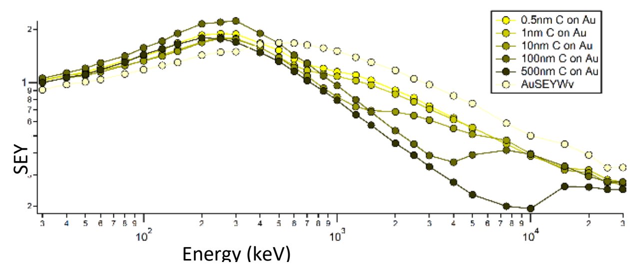


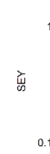
Figure 10. Layers of gold of with thicknesses ranging from 1nm to 100 nm on top of graphitic carbon.[1]

gold peak. Over the next nine months two more data sets were taken, the yellow data set after five months and the green data set four more months after that. The contamination layer continued to grow, and it can be seen clearly in the graph. The carbon peak gets higher and higher and the gold peak begins to vanish. This is because it only takes a thin layer of contamination at low energies to mask the yield of the base material.

In many situations it is not possible to avoid or remove contamination. Therefore, when considering the yield of a material to be used, it is important to consider the contamination layers it is likely to develop. Using yield measurements of a contaminated surface will give more accurate performance than a pristine material.

Using thin films, we can create layers to our advantage. A common method of lowering the yield of a material is to coat it with a thin layer of another material with a lower yield. This allows for a spacecraft to be built out of whatever material is preferred then coated with an appropriate coating to reduce the yield.

Figure 9 shows a set of electron yield measurments taken on a gold sample with different thicknesses of graphitic carbon layers on top1. Because carbon's electron yield is lower than gold it lowers the yield. Even a layer as thin as half a



nanometer has an appreciable affect on the electron yield. The thicker the carbon layer the lower the yield. This is directly related to the pentretation depth of the incident electrons. At higher incident energies the electron yield curve transitions to a more gold like curve. This is because the incident electron is pentrating through the surface layer and interacting with the gold underneath. Where this transition happens depends on the thickness of the carbon layers. In the same study layers of gold were placed on top of graphitic carbon (See figure 10). In this case the gold layer on top raised the electron yield curve, because of its higher electron yield.

Conclusion

It is unlikely any material used in a real-world application will have an electron yield equivalent to a pristine version of itself. Even if a material starts in a pristine state, charge neutral, perfectly smooth, and with no contamination layers. It will likely change as it is exposed to its environment. To get the most relevant electron yield for a material the real-world environment needs to be taken into consideration.

There have been many studies done over the years on the electron yield of different materials with different surface modicfications. By understanding each of these modifications and their influences, it will be possible to select appropriate studies to more accurately describe a given material's performance in its real-world environment.

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