SECONDARY ELECTRON EMISSION
FROM DIELECTRICS

by


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IN
PHYSICS

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MASTER OF SCIENCE
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This project involved the design and construction of an experiment to measure secondary electron emission coefficients of dielectrics. Data were taken on samples of Lexan, Lucite, treated Lexan, and treated Lucite. Two sets of data were taken for each sample. The samples were chosen based on previous experiments conducted in the surface flashover laboratory that indicated interesting properties of the treated samples. Due to the difficulties involved in measuring secondary electron emission coefficients of dielectrics by traditional means, a new technique was developed to enable the measurement to be conducted while using the surface charge to control the incident electron beam energy. The technique was successful in obtaining data for the lower energy region of the SEE coefficient curve.

The introduction in Chapter 1 gives a definition of secondary electron emission coefficients, their significance, and a summary of previous work. A brief discussion of the elementary theory of secondary electron emission is given in Chapter 2. Chapter 3 outlines the design and construction of the experimental set-up used to make the measurements. The data, and the calculations necessary to obtain it, are presented in Chapter 4.
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CHAPTER 1
INTRODUCTION AND BACKGROUND

The surface of a solid, when bombarded by electrons, may emit electrons by a process known as secondary electron emission. Part of the primary electrons that strike the surface will be elastically reflected and will have an energy equal to that of the incident electrons' energy. The electrons that are not elastically reflected will penetrate into the material. It is these electrons that are responsible for the secondary emission process. The secondary electrons that leave the material are referred to as "true" secondaries if they have energies of 50 eV or less. The electrons that leave the sample with energies of 50 eV or greater are considered to be inelastically reflected primary electrons that leave the sample by means of some scattering process. The choice of 50 eV as the distinction between secondary and backscattered electrons is arbitrary, but it is the accepted convention in the literature.

The electrons leaving the sample thus fall into three categories:

1. elastically reflected primaries
2. inelastically reflected primaries
3. "true" secondaries

The ratio of the number of electrons leaving the sample to the number of electrons incident on the sample is referred to as the total yield, $\sigma$. The ratio of the true secondary electrons to the primary electrons is referred to as the secondary electron emission, or SEE, coefficient, $\delta$. A relationship between $\sigma$ and $\delta$ may be written as:

$$\sigma = \delta + \eta,$$
where $\eta$ is the ratio of elastically and inelastically reflected electrons to the primary electrons. The above convention is a fairly recent one, and $\sigma$ and $\delta$ are frequently interchanged in the literature. It is also common to see $\delta$, the secondary electron emission coefficient, defined as the total yield. This inconsistency in notation is confusing, but it is not significant because $\sigma$ and $\delta$ usually differ at most by a few percent for low energy primary electrons. At higher electron energies, even fewer electrons are reflected, and $\sigma$ and $\delta$ are roughly equivalent. This usually holds for energies from 100 eV to 50 keV. [1]

The total yield was measured in this experiment. To be as consistent as possible with the sources quoted in this thesis, the total yield will be used interchangeably with the term secondary electron emission coefficient and will be denoted by $\delta$.

The SEE coefficient of a material is generally given as a function of primary electron energy. Figure 1.1 is a qualitative example of the general appearance of a SEE curve. The maximum value of the secondary electron emission coefficient is $\delta_{\text{max}}$. It occurs at an energy which is characteristic of the material, $E_{\text{max}}$. In metals, $\delta_{\text{max}}$ is usually not much greater than 1. In insulators, $\delta_{\text{max}}$ can take on values of 10 or more, but it is usually about 3 or 4. A $\delta$ value of 4 would mean that there are four times as many electrons leaving the sample as there are incident on the sample.

Two other points of interest on the energy scale of Figure 1.1 are $E_{\text{I}}$ and $E_{\text{II}}$, the first and second crossover points. These are the energies at which $\delta$ has a value of 1, and the electron current leaving
Figure 1.1 Qualitative example of a secondary electron emission versus incident beam energy curve
the sample is equal to the primary beam current. The first crossover
to point, as well as the overall shape of the SEE curve, is unique to the
particular material.

The primary motivation for this work originated with some previous
The surface flashover potential of an insulator is the potential
difference across an insulator surface at which the surface of the
insulator breaks down and an arc occurs. Jackson observed a significant
increase in the surface flashover potential of polymer samples, in
particular polymethylmethacrylate (Lucite) and polycarbonate (Lexan),
when the samples were irradiated with a spark plug. Surface flashover
of insulators has been an area of considerable research. Current models
assume that the surface flashover potential is related to the SEE coeffi­
cient of the material. The breakdown voltage as a function of the
first crossover point was given by Hackam and Pillai [3]:

\[
V_B = \left( \frac{M_{CR}E_I v_0 e I}{2 \varepsilon_0 \gamma v e \tan \theta} \right)^{1/2}
\]

- \( M_{CR} \) - critical mass of described gas atoms required to get a Townsend breakdown
- \( V_B \) - breakdown voltage
- \( E_I \) - first crossover point
- \( v_0 \) - velocity of described gas atoms
- \( \gamma \) - gas desorption coefficient
- \( e \) - electron charge
- \( \varepsilon_0 \) - permittivity of free space
\[ v_e \text{ - average velocity of electrons emitted from a site} \]

\[ \tan \theta = \frac{E_\perp}{E_\parallel} \text{ field due to surface charge } \]

\[ \text{applied external field} \]

The energy \( E_\perp \) is the first crossover point of the secondary electron emission coefficient curve. A surface breakdown occurs due to the surface charging of the insulator by the SEE process and due to the presence of a layer of desorbed gas molecules near the surface of the insulator. In this work, the SEE coefficient was measured for Lexan and Lucite, both treated and untreated samples. The surface flashover potentials of these materials are known from Jackson's work, and a measurement of the SEE coefficient will, hopefully, aid in the analysis of the reasons behind the increased surface flashover potential in the treated samples.

There has been one previous attempt to experimentally correlate the surface flashover potential of a material with its SEE coefficient. Chatterton and Davies [4] conducted a series of measurements of both parameters on samples of coated and uncoated \( \text{Al}_2\text{O}_3 \). The results of their SEE coefficient measurements indicated that samples with a lower SEE coefficient exhibited a higher surface flashover potential. Both measurements were conducted in the same experimental chamber. For the SEE measurement, a cylindrical electrode inside the chamber was used to collect the secondaries emitted by the sample. The system required a high degree of symmetry of the biased collector to determine the field acting on the beam and, therefore, the effective electron energy at the sample surface.

There has been very little work to date on the SEE coefficient of
polymers. Some of the earliest work was done by Matskevich [5] in the early 1950's. He measured the SEE curves of a number of polymers including Lucite. His original curve is shown in Figure 4.3.

More recent work has been done by Willis and Skinner [6] who measured the SEE coefficient of thin polymer foils. Their data are pictured in Figure 1.2. The authors used a small, pulsed current of $10^{-9}$ Amperes and neglected any surface charging effects based on the assumption that their foils were thin enough to leak off any surface charge between pulses.

One of the difficulties encountered in obtaining an experimental curve for SEE coefficients is that there are many factors which can influence secondary electron emission. Polymers present a particular problem for several reasons. There are different processes used to manufacture bulk polymer materials, all requiring the use of different solvents which remain present in small amounts as contaminants in the final product. In this work, samples were taken from the same bulk batches used by Jackson to allow correlation of the SEE data with Jackson's surface flashover data.

Polymers are also easily damaged by the electron beam used in the experiment. This damage affects the surface properties of the target sample. Chatterton and Davies [4] illustrated the effects of this damage on the SEE coefficient as shown in Figure 1.3. A cylindrical macor sample was irradiated with an electron beam at a reference point. The SEE coefficient was measured around the whole cylinder from $-180^\circ$ to $+180^\circ$ with $0^\circ$ being the point on the circumference that had been radiation damaged. For this reason, it is desirable to use as small a
Figure 1.2 Secondary electron emission coefficients of some polymer foils
Figure 1.3  Effects of electron beam irradiation on the SEE coefficient of Macor.
current as possible to minimize the damage.

Another problem with dielectrics in general is the surface charge that forms when $\delta$ is not equal to 1. For $\delta > 1$, more electrons leave the sample than are incident on its surface, resulting in an accumulation of positive charge on the sample surface. This positive charge makes it difficult to define the potential at the sample surface. Very recent experiments also indicate that at high energies (1 keV and greater), the surface charge may influence the SEE coefficient [7].

The SEE of polymers is also temperature dependent. The theoretical basis for the temperature dependence of the SEE coefficient for insulators in general is given in Chapter 2. In addition, polymers undergo a glass transition at some temperature to a completely disordered state. The SEE of polyethylene as a function of temperature and for a particular beam energy was measured by Ueno and Sugita [8]. They found that the energy distribution of the secondaries changed as a function of temperature.

There are other factors that influence the secondary electron emission of all materials. The SEE coefficient measured for thin films has been found to depend on the film thickness. Secondary electron emission was used as a means to determine film thickness by Okamoto [8]. His results for the yield versus thickness relationship for oxide films 20A to 200A thick are shown in Figure 1.4.

Most previous measurements of the SEE of polymers were made on thin films to avoid the problem of surface charging previously described. The work by Okamoto, however, indicates that not only does the SEE coefficient depend on film thickness, but that surface charging becomes a
Figure 1.4  SEE versus thickness relationship for SiO$_2$ films. (Arrows indicate the onset of charging effects)
factor when the film thickness exceeds 200 angstroms. This indicates that the use of a thin film is not an effective way to determine the SEE coefficients.

Secondary electron emission has also been shown to depend upon the angle of incidence of the primary beam. Salehi and Flinn compared SEE yield curves of an amorphous material for various angles of beam incidence [9]. The results of their measurements are given in Figure 1.5. The secondary electron emission becomes greater for larger angles of incidence and $\delta_{\text{max}}$ shifts to a higher energy value.

In addition to the work that has been done to correlate SEE curves with various parameters, much effort has been focused on obtaining the curve itself for various materials. Data can be found in the literature for most common metals and semiconductors and some insulators. Data on organic insulators, particularly polymers, have not been widely available to date. The goal of this work was to develop a new technique to measure the secondary electron emission coefficients of insulators. An experiment was designed and constructed to obtain such measurements. The technique used is detailed in Chapter 3. Data was taken for Lucite, Lexan, treated Lucite, and treated Lexan, and the results of the data are presented in Chapter 4.
Figure 1.5 SEE yield curves for various angles of incidence

$V_2O_5 - P_2O_5 - Cs_2O$ (50-20-30)
CHAPTER 2
THEORY OF SECONDARY ELECTRON EMISSION

Secondary electron emission in metals is fairly well understood and SEE curves are usually available. For insulators, however, both the theory and the experiment are difficult. The unavailability of data and some of the experimental problems were discussed in Chapter 1. This chapter will present the basic theory of secondary electron emission and recent attempts to apply this basic theory to insulators and specifically polymers.

Bruining [10] was one of the first investigators to work on the elementary theory of secondary electron emission. He also reported some experimental work. The SEE curve for graphite, used in this project for current calibration, was first obtained by Bruining. Most of his experimental work was done in the late 1930's and early 1940's. Dekker [11] expanded on the elementary theory of Bruining and others. Many current theoretical works on secondary electron emission still use both experimental and theoretical results presented in Bruining's book published in 1954 and in Dekker's [1] book published in 1957 with only minor modifications. The goal of most theoretical work is to obtain a method to give a universal SEE curve for all materials. The elementary theory makes five basic assumptions:

1. Elastic and inelastic scattering of the primary electrons is neglected.
2. The primary beam is incident perpendicular to the surface of the material.
3. The energy loss per unit path length follows Whiddington's Law:
4. The number of secondaries produced in a layer $dx$ is proportional to the energy loss:

$$n(x) = \frac{1}{\epsilon_e} \frac{dE_p}{dx}$$

$n(x)$ - number of secondaries in a layer $dx$ at depth $x$

$\epsilon_e$ - excitation energy required to produce a secondary electron

5. The escape probability for a secondary electron at a depth $x$ is given by:

$$f(x) = f(0)e^{-\frac{x}{x_s}}$$

$f(x)$ - escape probability from depth $x$

$f(0)$ - escape probability from the surface

$x_s$ - average range of the secondaries

Using these five basic assumptions, $\delta$ can be written as the integral of the product of the number of secondaries produced at the depth $x$ and the probability that they will escape:

$$\delta = \int f(x)n(x)dx$$

For the very low primary beam energies, the secondaries will have a greater range than the primaries, and their escape probability can be assumed to be a constant equal to the escape probability at the surface. The expression for $\delta$ then becomes:
\[ \delta = f(0) \frac{E_p^0}{\varepsilon_e} \]

\( E_p^0 \) - primary beam energy at the sample surface

At very high energies the expression for \( \delta \) can be estimated by:

\[ \delta = \frac{A}{\varepsilon e^0} \frac{f(0)}{x_s} \]

This expression was found by assuming that the production of secondaries \( n(x) \) is constant over the range of significant depths.

\[ n(x) = n(0), \]

where \( n(0) = \frac{A}{\varepsilon e^0} \)

These expressions were further developed by several investigators who obtained universal curves for \( \delta \). Figure 2.1, taken from Dekker [1], shows two such universal curves and their comparison with measured experimental data points. The failure of the curve to match experiment at higher energies is thought to be due to the production of secondary electrons by inelastically scattered primaries as they leave the sample.

The physical mechanism responsible for the production of secondary electrons in metals is the transfer of energy by the primary electrons to the conduction electrons in the metal. If these conduction electrons receive enough energy to overcome the work function of the metal and the losses encountered due to interactions with the lattice, they may be emitted as secondaries [1].

The physical process behind the production of a secondary electron in insulators is poorly understood. The energy required for a secondary electron to escape the material is determined by the electron affinity of the insulator and the losses suffered by the electron due to
Figure 2.1 Example of universal curves for SEE coefficients for metals
interactions with lattice vibrations. The lattice vibrations in metals are not of a significant order of magnitude; but, in insulators, they dominate over other interactions. This is the reason for the temperature dependence of the SEE coefficient of insulators.

Recent investigators suggest that a constant loss law raising $E_p(x)$ to some power $(n-1)$ as first proposed by Baroody [12] provides a better fit with experiment:

$$\frac{-dE_p}{dx} = \frac{A}{E_p(x)^{n-1}}$$

Most metals, semiconductors, and insulators are best described by the value of $n=1.35$. An interesting phenomenon noted by Willis and Skinner [6] and illustrated in Figure 2.2, is that polymers are best described using the value $n=2$ first proposed in the elementary theory.

A detailed analysis of the universal curve parameters was conducted by Dionne [11] for the purposes of relating the parameters $A$, $\frac{1}{x_s}$, and $\varepsilon_e$ to material properties. Dionne found that $A$ was directly proportional to the material density, and $\frac{1}{x_s}$ was determined by the electrical conductivity and $\varepsilon_e$, the average excitation energy required to produce a secondary, was proportional to the sum of the band gap and the electron affinity of the insulator. The band gap also determines the conductivity of the insulator, so it influences $\frac{1}{x_s}$. Therefore, it is possible to have a large band gap and still a high SEE yield.

Dionne's work was significant because it was the first attempt to
Figure 2.2: Reduced SEE versus primary beam energy plot for polymer foils.
relate parameters that were previously adjusted to fit the data to actual physical properties. The meaning of the role played by the power \((n-1)\) in the energy loss expression is still not physically understood. In general, the theory remains highly empirical and provides, at best, a fair fit to experimental data.
A block diagram of the experimental arrangement is shown in Figure 3.1. There are two independent vacuum chambers. The lower chamber contains the samples and is pumped by a 4 inch diffusion pump with a liquid nitrogen cold trap. The pressure obtained with the cold trap filled is about $5 \times 10^{-7}$ Torr. The upper chamber contains the electron gun and is pumped by an ion pump. It is kept under a vacuum at all times at a pressure of about $2 \times 10^{-7}$ Torr to avoid oxidation of the electron gun cathode. The lower chamber may be opened to the atmosphere to change samples without disrupting the vacuum in the upper chamber by closing the air operated gate valve separating the two chambers.

The lower chamber contains the sliding sample holder. It is operated manually using a linear motion vacuum feedthrough and measured with a caliper to determine the location of the samples in the chamber. The sample holder is Lucite mounted on an aluminum track. Figure 3.2 illustrates the sample holder. The samples are placed on metal holders attached to the Lucite by small bolts, but isolated electrically from each other. The bolt head makes an electrical connection with a spring finger that is connected to the cable leaving the chamber by a BNC connector. The Lucite holder may be removed without disturbing the aluminum track; therefore, it is realigned to the same position each time the samples are changed. The average pumpdown time in the lower chamber is about two days. The long pumpdown time is due to the outgassing of the polymer samples and the silver paint used to hold them to the sample holders.
Figure 3.1 Block diagram illustrating experimental arrangement
Figure 3.2  Sample holder
The upper chamber contains the electron gun made from a cathode ray tube. It has two seven pin electrical feedthroughs to control the tube voltages. The average pumpdown time in the upper chamber was also about two days.

The CRT is supported by a stainless steel tube mounted on a stainless steel sheet with a 2 mm aperture for the beam. This tube is suspended from the top flange by stainless steel rods isolated electrically from the chamber by ceramic spacers. The stainless steel sheet, referred to from here forward as the mask, was connected to a current meter for reasons to be described later. The CRT holder is illustrated in Figure 3.3.

The external circuit controlling the CRT is depicted in Figure 3.4. The circuit enables the tube to supply a beam within a wide energy range by operating the tube at different voltages. The lower limit on the beam energy is about 400 eV, whereas the upper limit was undetermined, but was greater than 1600 eV. The normal operating voltage in this experiment was about 1100 V.

The controls are set up to yield either a continuous or a pulsed current. A continuous current is obtained by biasing the grid negative with respect to the cathode and increasing the voltage between the grid and the cathode until the desired current is obtained. An example of the settings required to get a current of $1 \times 10^{-10}$ amperes with a beam energy of 1063 eV is given below:

- Grid voltage: -1100 V
- Cathode voltage: -1063.2 V
- Focusing anode voltage: -704.1 V
Figure 3.3 CRT holder
Figure 3.4 Circuit diagram for circuit controlling CRT
The CRT is also connected to a pulse generator to allow the experiment to be conducted using a pulsed current. In this case, the grid is set to a cutoff voltage so that no current is supplied by the tube, and is pulsed positive by a pulse generator. The amplitude of the pulse determines the current magnitude.

The deflection plates are controlled by two power supplies connected as shown in Figure 3.5. The controls are such that for a given voltage setting, the plates will have a voltage equal in magnitude but opposite in polarity. A switch allows the polarity to be reversed. There are two sets of deflection plates and they are controlled in the same manner. Typical voltages required to steer the beam to the sample were about 3 to 10 volts.

To obtain an electron gun from a CRT, both the fluorescent screen and the base of the tube must be removed. The pin connectors at the base of the tube were cut off to remove any solder holding the tube wires to the base. The base was removed by dissolving the adhesive holding it to the tube in a methyl ethyl ketone solution. The flared end of the tube was scored just above the flare and a high resistance nichrome wire was gently squeezed around the tube. A variable transformer was used to slowly raise the current in the wire, increasing its temperature and causing the wire to expand. When the current was cut off and the wire contracted, the tube broke due to the stress induced by the rapid heating and cooling.

The tube wires were connected to the feedthrough by spot welds and the tube was held firmly in the tube holder by placing fingerstock between the tube and the holder walls. The tube was left in a vacuum
Figure 3.5 Circuit controlling deflection plate voltages
for several days to outgas and only after a consistent low pressure ($2 \times 10^{-7}$ Torr) was obtained was the cathode activated.

During the brief time that the cathode was exposed to the atmosphere, the rare earth metals of the cathode oxidized and absorbed gases from the atmosphere. These compounds must be decomposed and the rare earth metals exposed to give a good electron beam. This was done by slowly increasing the heater voltage to its maximum value of 6.3 V. The voltage was increased in steps of about .2 V with a few minutes between steps to allow the pressure to stabilize. When a voltage of about 4.5 V was reached, a 1.5 V battery was placed between the grid and the cathode to see if the cathode was emitting electrons. A current of about 2 microamps was observed, which steadily rose as the heater voltage was increased. A floating microammeter in series with the cathode was used to monitor the current leaving the cathode. After the current stabilized and was constant over a period of time, the tube was assumed to be completely activated and ready to supply the electron beam to the samples.

The electron beam was adjusted to hit the sample using a number of techniques. A graphite sample was first placed as a target, since the SEE coefficient of graphite was known for a large range of energies. Using this as a calibration, it was possible to determine the amount of current striking the graphite. This current was measured with a Keithley 610C electrometer. In addition, a current meter was hooked to the mask to measure the current striking the mask.

To position the beam at the center of the sample required adjustments of the steering plates and the focusing anode while monitoring the
current on the mask and the graphite. The focus is initially set to the approximate voltage given in the CRT characteristics. The deflection plates voltages are adjusted to give a minimum current reading on the mask and a maximum reading on the sample. The focus is then set to give a minimum current on the mask (ideally zero current) and a maximum current on the sample. After the maximum current is read on the graphite, it is undesirable to focus the beam any more because the beam diameter will become smaller than the sample diameter. If the beam diameter is roughly equivalent to the sample diameter, the linear slider of the sample holder can be moved a small amount and the meter reading the current on the graphite will indicate a reduction in the current reaching the graphite. In summary, there are several ways to insure that the current strikes the sample: monitoring the current on the mask and the sample while adjusting the deflection plates, maximizing the current on the sample by adjusting the focus, and observing the current drop if the sample is moved a small amount. Obviously, the beam will not be a perfectly uniform spot, exactly covering the sample. The significance of the error introduced by nonuniformities of the beam is discussed in Chapter 4.

As previously discussed, it is necessary to use samples taken from bulk polymer material to apply the results to previous work done on these materials. The samples are cut from a bar, 10 cm in diameter, to a thickness of 1 cm, and then milled to a square shape to give a flat edge. They are polished with toothpaste and 100 micron alumina grit and cleaned with cyclohexane, a solvent which cleans without damaging the sample surface or leaving a residue. The samples that are treated must
not be touched because preliminary tests indicate that the treatment layer is very thin and susceptible to damage by mechanical abrasion. The samples for this experiment were supplied by the surface flashover laboratory. A 1.9 mm slice is cut from the square samples. A 9.5 mm hand held hole punch is used to punch a round sample from the thin slice. This method allows the round sample to be obtained without any physical contact with the surface. The back surface of the samples is painted with silver paint which acts as an adhesive and provides the electrical contact with the sample holder. The graphite sample is taken from a thin sheet of very pure, high quality graphite, 5 mils thick. It is also punched from the thin sheet, after which it is rinsed in ethyl alcohol and placed on the sample holder with an Aquadag solution. The hole punch causes the edges of the polymer samples to be rough, particularly the Lucite, which is brittle. This introduces a smaller error than if the sample had been handled on its surface.

Before detailing the measurement circuit, it is necessary to discuss the nature of the measurement and some of the difficulties encountered in measuring secondary electron emission in dielectrics. In metals, the general approach taken has been to strike a sample with electrons and let the surrounding chamber be a collector to measure the current collected. This introduces a small error due to the fact that the chamber itself may produce secondaries. In general, the chamber used is a highly symmetrical chamber, either spherical or cylindrical. This method presents a problem when an insulator is used as a target. The insulator becomes positively charged in the energy region where $\delta > 1$, and the field in the chamber becomes distorted. Many of the secondaries
will have such a low energy that they will be drawn back to the sample surface. In addition, since the whole chamber acts as a collector, it is impossible to accommodate more than one sample of insulator material without shielding the additional samples, making the field more difficult to define. A well defined potential is essential in order to calculate the energy possessed by the electrons when they strike the sample surface.

In this experiment, the sample was biased negatively to repel the low energy secondaries. The current meter hooked to the back of the sample measures the net current on the sample surface. In the region where the SEE yield is greater than one, the net effect at the sample surface will be a current of electrons leaving the sample. As electrons leave the sample, the surface accumulates a positive charge. If the sample is viewed as a parallel plate capacitor, the change in potential at the sample for a given amount of charge $Q$ is $V = \frac{Q}{C}$. In order to model more quantitatively, consider the following parameters:

- $I_b$ - electron beam current (primary current)
- $I_s$ - secondary electron current
- $I_o = I_s - I_b$, net current at surface
- $E_b$ - incident electron beam energy
- $V_o$ - bias voltage
- $V_s$ - potential at sample surface
- $C_s$ - sample capacitance

By definition, $\delta = \frac{I_s}{I_b}$. 
but \( I_s = I_o + I_b \)

so \( \delta = \frac{I_o + I_b}{I_b} \) \[3.1\]

The current, \( I_o \), is a measurable quantity. It is the goal of this experiment to obtain \( \delta \) as a function of energy. The energy of the electrons incident on the sample surface is:

\[ E_o = E_b - V_s \]

The potential at the surface:

\[ V_s = V_o + \Delta V \]

where \( V_o \) is always negative. The quantity \( \Delta V \) is the change in potential of the sample surface due to the accumulation of charge \( \Delta Q \) on the surface.

\[ \Delta V = \frac{\Delta Q}{C} \]

\( \Delta Q \) is time dependent and is determined by the amount of current leaving the surface.

\[ \Delta Q = \int I_o \, dt \]

The equation for \( E_o \) now becomes:

\[ E_o = E_b - V_o + \frac{1}{C} \int I_o \, dt \] \[3.2\]

Equation 3.2 shows that if \( I_o \) is a known function of time, one can calculate \( \delta \) and \( E_o \). Neglecting stray and leakage effects, the circuit can be modeled as illustrated in Figure 3.6. The CRT is shown as a continuous current source and \(-V_G\) is the voltage applied to the grid of the CRT.

The bias box is constructed using three 510 V dc batteries. A switch enables the use of one, two, or all of the batteries to bias the
Figure 3.6  Equivalent circuit of CRT, sample, and electrometer
sample, giving a choice of where to begin the measurement. Initially, the box was built using a simple design insulating the batteries from a grounded metal box; however, the leakage resistance of this configuration, as well as the noise level, was not tolerable. A more sophisticated design was employed to give a longer leakage path from the battery to the box. This design is pictured in Figure 3.4. The leakage current was still fairly high, $3 \times 10^{-11}$ amp, but the noise level was much better. The current measurement was made using the Keithly 610C electrometer in the feedback mode. The response time of this meter at the desired level is about one second. The meter output is hooked to a strip chart recorder which plots the current read by the meter with respect to time. The electron current used in this experiment was 1 to $5 \times 10^{-10}$ amperes.

To relate the current plotted by the chart recorder to $I_o$, the current used in equations 3.1 and 3.2, it is necessary to consider all of the stray and leakage effects. Figure 3.7a gives an equivalent circuit of these effects.

The capacitance, $C_1$, is the total stray capacitance of the sample holder, the cables, the bias box, and any other stray capacitances present in the measurement circuit. It appears in parallel with the bottom plate of the sample. The capacitance between the top of the sample and the grounded chamber walls is $C_2$. The leakage resistance of the bias box is $R_1$. The electrometer uses an operational amplifier to drive the voltage of the electrometer input to zero. Because of this feature, the stray capacitance, $C_1$, is insignificant and the charge is constant on this capacitor. Therefore, all of the charge will divide
Figure 3.7a: Equivalent circuit including stray and leakage effects.

Figure 3.7b: Models used to calculate stray capacitance
between \( C_s \) and \( C_2 \). To determine the magnitude of \( C_2 \), two models are employed, pictured in Figure 3.7b.

Model 1 uses a parallel plate approximation with \( C_2 = \frac{\varepsilon A}{d} \), where \( A \) is the sample surface area, and \( d \) is the distance between the sample surface and the part of the chamber directly above the sample. This gives a value for \( C_2 \) of approximately 0.8% of \( C_s \). Obviously this approximation underestimates the value for \( C_2 \).

Model 2 uses a concentric sphere model with \( C_2 = \frac{4\pi\varepsilon_a b}{(b-a)} \). The radius, \( a \), is taken as the sample thickness and \( b \) is taken as a very crude average distance between the sample and the chamber. This approximation gives \( C_2 \approx 0.08C_s \). This model overestimates \( C_2 \) since the sample surface is not at all spherical and is not exposed to all of the chamber walls. It is assumed that \( C_2 \) introduces an error somewhere between the two approximations of 3 - 4%. This is neglected because it is less than the error in the measurement itself.

The leakage resistance, \( R_L \), is responsible for a constant leakage current, \( I_L \). This current is used as the zero point on the chart recorder paper, so it is automatically subtracted out of the measurement.
CHAPTER 4

DATA AND CONCLUSIONS

The data are obtained in the form of a chart recorder plot of $I_o$, the net current at the sample surface, versus time. The change in the slope of the curve indicates the amount of time required for the electrometer to respond with a current measurement. The curve shows this time to be about .5 sec. to 1 sec. and this point is taken as the $t = 0$ point in the calculations. Calculation of the $\delta$ versus primary beam energy required the integration of the $I_o$ versus $t$ curve, as obvious from equation 3.2:

$$E_o = E_b - \left[ V_o + \frac{1}{C} \int \Delta I_o \, dt \right]$$

The data plot was divided into .5 second intervals. The average current during the time interval was scaled from the chart recorder plot. The last part of equation 3.2 can be written as

$$\frac{1}{C} \int I_o \, dt = \frac{1}{C} \sum I_{avg} \Delta t$$

where $\Delta t$ is 0.5 sec. and $I_{avg}$ is the average value of $I_o$ for each $\Delta t$ interval. The energy of the primary beam as it strikes the sample surface can be calculated for each time using

$$E_o = E_b - V_o + \left[ \frac{\sum I_{avg} \Delta t}{C} \right]$$

and $\delta$ for the same time is given by

$$\delta = \frac{I_{avg} - I_b}{I_{avg}}$$

This calculation was done in succession for each $\Delta t$ interval to give a
series of data points for the $\delta$ versus $E$ curve.

In the model derived in Chapter 3, it is assumed that the sample acts as a parallel plate capacitor. This assumption is made solely for the purpose of calculating the potential at the sample surface, $V_s$. The energy of a primary electron as it strikes the sample surface is determined by the initial beam energy and the sample surface potential. For this reason, it is important to have an accurate means of determining the sample surface potential. The parallel plate model was used because it is a good representation of the physical situation.

When using the parallel plate model, it is assumed that the electron beam strikes the sample uniformly, thereby creating an even distribution of charge on the surface. This is probably a good approximation; however, it is possible that the beam is not exactly circular, and/or not uniformly distributed. Figure 4.1 illustrates a possible non-uniform charge distribution. The charge is plotted as a function of radial distance from the center of the sample. The error resulting from any non-uniformities in the charge distribution does not affect the calculation of $\delta$, since

$$\delta = \frac{I_o - I_b}{I_o}$$

and the same value of $I_o$, the net current, is obtained from the electrometer regardless of where the beam strikes the sample. Any error that does result due to beam non-uniformities will affect the calculation of the sample surface potential.

To evaluate the significance of this error, the following model can be employed:
a.........sample radius
R.........distance from center
of sample
σ.........charge density

Uniformly distributed charge

Nonuniformly distributed charge

Figure 4.1  Illustration of uniform and nonuniform charge distributions
Consider a uniformly charged disk of radius $a$. The potential due to the disk at an axial distance $R$ is given by:

$$V = \frac{\rho}{2\varepsilon_0} \left( \frac{a^2}{\sqrt{a^2 + R^2}} - R \right)$$

$a$ - the radius of the disk

$R$ - the distance from the center of the disk

$\rho$ - charge per unit area

$\varepsilon_0$ - permittivity of free space

If $\sqrt{a^2 + R^2}$ is expanded and only second order terms are retained, the potential reduces to that of a point charge:

$$V = \frac{1}{4\pi \varepsilon_0} \frac{q}{R}$$

$q$ - the magnitude of the point charge

In this experiment, $a = .5$ cm and $R = 25$ cm, therefore, for most of its path, the electron sees only a point charge and any non-uniformities in the charge distribution are insignificant.

An additional source of error in the parallel plate model is the assumption that the charge remains on the surface of the dielectric rather than embedded in it. For the energies considered in this experiment ($< 1100$ eV), a penetration depth of $10 - 20$ nm [13] can be assumed. The bulk sample is $2$ mm thick, several orders of magnitude greater than
the penetration depth of the electrons. All of the charge was considered to be on the surface.

Data was taken on two separate occasions. During the current calibration procedure described in Chapter 3, it was discovered that the SEE curve for graphite, given by Bruining [10] in 1938, was not consistent with the observations made in this experiment. At energies of less than 400 eV, $\delta$ for graphite was observed to be substantially greater than one. This was obvious from the indication of a positive current by the electrometer. A positive current occurs when more electrons leave the sample surface than are incident on it, the condition necessary for $\delta$ to be greater than one. Bruining's curve gives a maximum for $\delta$ of about 1.05, not a large enough value to give the magnitude of current that was observed. It is not known whether this effect was due to an error in Bruining's curve or a difference in the type of graphite used by Bruining and that used in this experiment. Because of this inconsistency, the current was calibrated at a beam energy of 1100 eV, a high enough energy to assume that Bruining's curve was correct. The value used for the current was further checked by comparing the SEE coefficient maximum of Lucite to the value of 2.4 given by Matskevich [5]. The numbers for $\delta_{\text{max}}$ agreed exactly.

The two data sets were taken two weeks apart. On each occasion, the samples were allowed to outgas and dry out under a vacuum for at least a week. Data were taken each time for the samples in the same order: Lexan, Lucite, treated Lexan, and treated Lucite. Several attempts were made to obtain more than one set of data for each sample. The first attempt to repeat the data on a previously tested sample was made about
one hour after the original data were taken.

Almost no current was observed, which indicated that very little of the charge on the sample had leaked off. On each occasion, a negative current was observed on the Lexan after the initial set of data. For reasons described above, a negative current will be observed if the SEE coefficient is less than 1. From Chapter 3, the sample surface potential is given by

\[ V_s = V_o + \frac{1}{C} \int I_o \, dt \]

When \( \delta = 1 \), the current leaving the sample, \( I_s \), is equal to the primary current, \( I_b \). The expression for the net current measured at the sample, \( I_o = I_s - I_b \), shows that no current will be indicated by the electrometer when \( \delta = 1 \). When there is no accumulation of charge at the sample surface, the potential remains constant at \( E_{II} \), the second crossover point. The negative current observed on the Lexan implies that the surface potential is at some energy above the second crossover point. From the arguments given above, the potential should reach a steady state at \( E_{II} \) not go above it. The rise in surface potential must be due to some other mechanism, possibly increased charging of the sample surface due to self-sustained secondary electron emission [14].

A second attempt was made to repeat the data on a previously tested sample after a twelve hour wait. The current \( I_o \) at \( t = 0 \) was less than the maximum current obtained in the first data set, and \( I_o \) decreased with time rather than peaking as it did in the initial raw data. This can be interpreted to mean that some of the charge had leaked off of the sample surface, allowing the SEE curve to be traced from some point in
energy greater than $E_{\text{max}}$ to the second crossover point. Only the first set of data per sample was used to calculate the SEE curve.

Data for the Lucite Sample #1 and Sample #2 were consistent enough to yield data points falling on a single curve. This curve for Lucite is thought to be easily reproducible. Figure 4.2 shows the curve obtained for Lucite from the two sets of data as well as the curve given by Matskevich [5] for Lucite. The magnitude and energy for $\delta_{\text{max}}$ agree, but the curves do not agree at high energies.

Figure 4.3 illustrates the data obtained for the two treated Lucite sample. Data set #1 gives a higher SEE coefficient for the treated sample than for the virgin sample. The shape of the curve is also different, with a much slower decrease in the SEE coefficient from $E_{\text{max}}$ to $E_{\text{II}}$. The energy value for $E_{\text{II}}$ for treated Lucite data set #1 could not be determined due to limitations in the rage of data that can be obtained in this experiment, but it can be said that it is greater than 1100 eV. The second set of data for treated Lucite produced a very different curve, one that is similar in shape to virgin Lucite. The lack of agreement between the data for the two samples indicates that some problem may exist with obtaining consistently prepared samples. Examination of the treated Sample #2 under a microscope revealed that to the best judgement that could be made optically, the sample was treated Lucite; however, it is possible that some error could have been made either in the treatment process or in the sample preparation.

The SEE curve obtained for Lexan is shown in Figure 4.4. The virgin Lexan was the first sample to be tested in both trials. For this reason it was the sample most susceptible to any initial mistakes made during
Figure 4.2 Data for virgin Lucite
Figure 4.3 Data for treated Lucite
Figure 4.4 Data for virgin Lexan
the course of the experiment. Unfortunately, there were problems on both occasions. For the first set of data, the electrometer was set to a scale that was too sensitive, and as a result, the chart recorder was driven off scale at the peak of the curve. The magnitude of $\delta_{\text{max}}$ was estimated by extrapolating the slopes of the part of the curve that was on scale and fitting the shape of the peak to that known to represent a standard SEE curve. The effect of any error present in this approximation is a shift of the whole curve to the left or the right on the energy scale; the general shape of the curve is unaffected.

The second data set for the Lexan was also plagued with initial experimental problems. When the electron beam current was decreased to its desired level, the electron gun ceased to produce a current at the time it was first incident on the Lexan sample. An unknown amount of charge was deposited on the Lexan sample. When the electron gun was restored to a stable operation, a much lower peak was exhibited by the sample than the peak observed in the previous experiment. Therefore, the data from Lexan Sample #2 was discarded, and the curve shown in Figure 4.4 is from data for Sample #1 only. The most questionable aspect of the curve is the magnitude of the peak and the energy at which it occurs.

The second set of data on treated Lexan was also difficult to interpret. The current decreased much slower than on the first set of data for treated Lexan, and it did not approach zero as expected, but rather the current approached a value of $6 \times 10^{-10}$ amp. Visual examination of the sample revealed that some of the silver paint used to hold the sample to the sample holder had contacted the edge of the sample in two
places. This provided a path for a leakage current to flow from the sample surface to ground. Further evidence was obtained to support this conclusion by repeating the data after a few minutes' wait. Unlike the behavior of the other samples, the SEE curve was completely retraced from the original starting point. This indicated that all of the charge had leaked off of the surface in about 10 minutes. The presence of the leakage current made it difficult to translate the raw data into an SEE curve. The curve for coated Lexan given in Figure 4.5 is for Sample #1 only.

Fortunately, no problems were encountered with the data on the first coated Lexan sample. The curve for coated Lexan is similar in shape to the SEE curve for coated Lucite. This is a very significant aspect of the data. Previous surface analysis conducted by Jackson [2] indicated that the chemical composition of the surface, as obtained by ESCA data, was the same for treated samples regardless of the bulk material used. Therefore, it can be expected that the SEE curves would appear similar if not identical, depending on the depth of the surface modification. For this reason, future data obtained for the treated samples are anticipated to resemble the curves from the first set of data.

The quantity \( \delta_{\text{max}} \) for the treated samples occurs at a higher energy than for the virgin samples. The peak in the SEE curve is smoother for the treated samples than for the virgin samples. This is further illustrated by looking at a plot of the reduced variables, 

\[
\frac{\delta}{\delta_{\text{max}}} \quad \text{and} \quad \frac{E}{E_{\text{max}}}
\]

as shown in Figure 4.6. The change in the slope of the curves at
Figure 4.5 Data for treated Lexan
Figure 4.6 Reduced variable plot for virgin Lucite, treated Lucite, and treated Lexan
-1200 eV is a consequence of the experimental method that was employed. The samples were negatively biased by a battery box at approximately 1100 eV to repel the low energy secondary electrons. When the surface has charged to the required value of \( Q = CV \), where \( V \) is the bias voltage and \( C \) is the sample capacitance, the surface potential is zero. This occurs when the effective beam energy is 1100 eV. The surface potential becomes positive for beam energies of 1100 eV or greater. The positive surface potential attracts the low energy secondary electrons back to the surface; therefore, the correct value for the primary current is no longer known. For this reason, a value cannot be obtained for the second crossover point for \( \delta \) for the treated samples.

One particularly interesting feature of the data shown in the reduced curve in Figure 4.6 is the value of the exponent in the power law representation of the exponential loss. This exponent determines the shape of the decay of the SEE coefficient after the peak. In Figure 2.2, a reduced plot given by Willis and Skinner [6] illustrated two universal curves, one with an exponent of \( n = 2 \) and one \( n = 1.35 \). Willis and Skinner point out that most polymers obey the \( n = 2 \) law, while most metals, semiconductors, and inorganic insulators obey the \( n = 1.35 \) law. From Figure 4.6, Lucite appears to behave as most polymers, while treated Lucite and treated Lexan resemble the exponential loss curve characteristic of inorganic insulators, metals, and semiconductors. This may suggest that the treated surface is no longer a polymer.

The shape and magnitude of the SEE curves for the first set of treated samples did not correlate with the surface flashover data as
expected. In previous work conducted by Chatterton and Davies [4], the investigators repeatedly observed in certain insulators that materials exhibiting a high surface flashover potential have lower secondary electron emission coefficients. For example, if a surface coating increased the surface flashover potential of a material, the secondary electron emission coefficient was lower for all energy values. In this experiment, the peak in the SEE curve for the treated samples was about the same as that for the virgin samples. In addition, for energies greater than $E_{\text{max}}$, the SEE coefficient for the treated samples was substantially greater than that for the virgin samples. The surface flashover potential for the treated samples, however, was greater than that for the virgin samples by 60% or more [2]. This is the opposite of the correlation observed by Chatterton and Davies. The reason for this lack of correlation was not obvious from the data obtained in this experiment. The results could have an impact on the theory of surface flashover since the current model inversely relates surface breakdown potential and secondary electron emission. If, however, the second set of data for the treated Lucite is an actual indication of the SEE curve for the treated samples, this serves to reinforce the model for surface breakdown.

The results for the SEE curves for treated Lucite and treated Lexan serve as a motivation to do additional work in this area. Both Delrin and polyethylene are known to exhibit a higher surface flashover potential as a result of the same surface treatment imposed on Lucite and Lexan. Blue nylon, however, shows a lower surface flashover potential after treatment. One would expect to see an effect in the treated
Delrin and treated polyethylene SEE coefficient as compared to the virgin samples similar to that observed in Lexan and Lucite. Blue nylon, however, might have a different behavior. Any differences observed in Blue nylon, as well as other materials on which the surface treatment does not increase the breakdown potential, could provide valuable insight into the relationship between surface flashover and secondary electron emission.

Additional future work can be done to refine the experiment and yield better resolution and accuracy of the SEE curve. The most important refinement involves the direct measurement of the charge on the sample surface rather than a measurement of the current. The experiment was designed to deliver a pulsed current if desired. The charge could be read by the electrometer in the coulombmeter mode after each current pulse. This would avoid any error introduced by graphically integrating the current versus time plot. The current could be calibrated by using a Faraday cup collector, particularly since unexpected discrepancies were discovered in Bruining's SEE curve for graphite.

As previously discussed, the curve obtained in this experiment is for energies up to about 1100 eV above which the positive surface potential causes secondary electrons to be recalled. Values of $\delta$ for energies greater than 1100eV were not considered as physically significant to the surface breakdown as those in the lower energy region of the curve. The quantity, $\delta$, can be obtained for such energy levels, however, by using a grid system to collect the low energy secondary electrons, or by employing a greater bias voltage. The important conclusion to be made from this experiment, however, is that this technique
does provide a method by which the secondary electron emission coefficient can be obtained for insulator samples taken from commercially available bulk materials.
LIST OF REFERENCES


