ELECTRONICS MANUFACTURE-ESD control-Electrostatics explained

Introduction

Static electricity is an everyday phenomenon – there can be few of us who have not experienced a static shock after walking across a room and touching the door knob, or on getting out of a car. We are also familiar with the crackle of static as we take off a fleece or other garment. Other static nuisance effects include the cling of some fabrics to the body, the sticking of a plastic document cover, or the attraction of dust to a TV or computer screen.

While we can feel some of these effects, static electricity is often present at lower levels that we cannot feel, hear or see, but may nevertheless damage sensitive electronic components. It can build up rapidly, in unexpected ways, to surprisingly high voltages that can lead to an electrostatic discharge (ESD) event.

Electrostatic charge

All materials are made up of positively charged atomic nuclei and negative electrons. Normally these charges are present in nearly equal quantities at any location, and their electrical effects neutralise each other. However, under some circumstances there can be an excess of one polarity at one location, matched by an equal but opposite polarity excess in some other region. The electrical effects of the charges are no longer balanced and a net static electrical charge exists at that location.

Electrostatic fields

Any charge has a region of influence around it, in which certain effects are noticed – this region is the electric field due to the charge. In the electric field:

- like polarity charges are repelled
- unlike polarity charges are attracted

Many static electricity phenomena are due to these basic effects on charges in surrounding materials. For example, a static electric field from a positively charged object will attract negative electrons to the surface of a nearby metal object within its field. Dust particles, free air ions and small objects are attracted or repelled by a field, especially if they are themselves charged.

If a positive and an equal negative charge are close together, from a distance their electric field effects cancel and no external field is noticed. The charges are said to be ‘neutralised’.

The strength of the electric field can fall off rapidly with distance r from a small charged object. For a point charge it is proportional to 1/r2. However, for larger objects, the fall-off can be less rapid, and regions of near-uniform field can exist.

Voltage or electrostatic potential

Charge is the fundamental source in static electricity1 , and electric field and voltage (more correctly, potential) are measures of the effect of the charge in the world around the charge source. Both field and voltage are considerably affected by the materials and proximity of nearby objects. Voltage is a measure of the potential energy at a point, and is perhaps analogous to pressure in a fluid system or height in a gravitational system. In fact voltage is strictly a potential difference, measured at a point compared to another point defined as zero volts. In practice, the potential of the earth (ground) is normally used as the reference.

1 An electron has a negative charge of 1.6x10-19 Coulombs. A proton in an atomic nucleus has an equal positive charge.

The voltage at a point, relative to ground, is by definition the energy required to move a unit charge from ground to that point. All points in space surrounding a charge have a voltage (potential) – typically this voltage will be different from its neighbouring points.

Like charges repel, and in a conductor where charges are free to move rapidly, charges will rapidly move to the outer surface to minimise their proximity to each other. After charge has redistributed, the voltage on all parts of the conductor is equal (equipotential). This must be so – current flows due to voltage differences, until the equipotential state is achieved.

For an insulating object, charge does not flow freely and so the voltage at each point on the surface is typically different from its neighbour.

For objects of high resistivity and long time constant, charge will redistribute to equipotential if we wait long enough (and if the field source is not changing rapidly) – but in the meantime surface voltages can be different.

Faraday cage

For a conducting object in an electric field, charge flows until all points on the surface are at the same voltage. If the object is hollow, then the field inside the object is zero, as it is surrounded by an equipotential conductor. An object placed within the hollow conductor would therefore be shielded from the effects of an external field. This hollow conductor is called a Faraday cage.

This effect is used in the design of shielding bags, to protect sensitive devices within the bag from electrostatic fields and direct ESD discharges. The bags contain a conductive thin metal film layer that acts as a Faraday cage. Shielding bags have the correct internal (‘intimate’) layer characteristics and shielding layer for protecting ESD sensitive devices outside the EPA.

A shielding bag is a laminated multilayer structure – a low charging static dissipative inner layer is in contact with the sensitive device. The shielding layer is a metallised film – thin enough to be transparent and yet thick enough to provide adequate ESD shielding. Some bags have an outer layer of dissipative material.

Contact charge generation (triboelectrification)

One major way in which static electrical charge can arise is when two materials, that are initially in contact, are separated. Whilst in contact, electrons move from one material to the other at points of contact – this material gains a net negative charge, and the donor material gains a net positive charge. When the objects are separated, the negatively charged object may take its charge with it, leaving an equal positive charge on the other object.

Although no charge is in fact generated, as only charge separation takes place, it is common to refer to the ‘generation’ of static electrical charge.

In practice, the amount of charge imbalance required to give strong electrostatic effects is surprisingly small. The limit of the amount of charge that can be built up on a surface is governed by the electrical breakdown field strength of air, around 3x106 V/m. The surface charge density required to give this field is only 2.64x10−5 cm−2. This is equivalent to about 1.7x1014 electrons/m2, or 8 atoms per million on the surface acquiring (or losing) an electron!

The polarity of charge

The polarity of charge left on a material can be positive or negative and depends on the other material with which it made contact. Materials may be arranged in a table according to the polarity of charge they take in contact with other materials. This is called the triboelectric series (see Table 1).

A material in the table (e.g. aluminium) can be expected to charge positively against another material below it in the table (e.g. PTFE) and negatively against a material above it (e.g. wool). The amount of charge generated is a function of the separation of the materials on the table; so aluminium and paper can be expected to charge relatively little against each other, but PVC and nylon can be expected to charge strongly against each other.

In practice the order of the triboelectric series is not unique and may differ between different experiments and samples. Triboelectrification is a very variable phenomenon, and is highly dependent on surface conditions, contaminants and humidity.

Table 1: An example of a triboelectric series

acetate	Charges to positive polarity
glass	↑
human hair	
nylon	
lead	
aluminium	
paper	
wood	
epoxy-glass	
copper	
stainless steel	↓
acrylic	
polystyrene	
polypropylene	
PVC	
silicon	
PTFE	Charges to negative polarity

Electrostatic charge build-up

It is important to understand that any two materials in contact will be subject to charge separation that can lead to static electrical charge build-up. This explains why static electricity is such a ubiquitous phenomenon. However, much of the time static electrical charge build-up is at a low level, as other effects often allow it to dissipate before a high voltage is built up.

The key to this build-up is the balance between charge generation and charge dissipation. If charge is generated more slowly than it can be dissipated, no static electricity builds up and no effects are noticed. If charge is generated even slightly faster than it can be dissipated, then high voltages and static electricity effects are quickly built up!

A simple electrical model of electrostatic charge build-up

Static electricity can be modelled as a charge generator, and a simple electrical model can be used to understand many practical situations (Figure 1).

Figure 1: Simple electrical model representing static electricity build-up

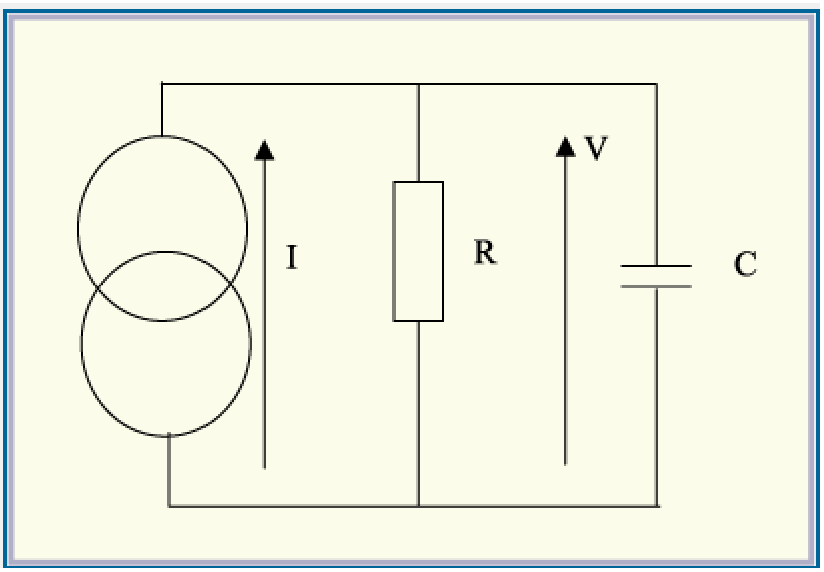

Figure 1: Simple electrical model representing static electricity build-up

The generation of charge is represented by a current source I. In practice, depending on the processes, real industrial sources can generate currents well over a microamp. The capacitor C represents the charge storage properties of the system, and could be a material surface or a conducting object with a capacitance to earth. The resistance R represents charge dissipation processes (other than non-linear ESD) and can be up to 1014Ω in the case of good insulators.

It's easy to see by Ohm's law that if charge generation rate of even 1mA (1mC/s) is present, with a resistance of 1010Ω, a steady state voltage of 10kV would be produced! Fortunately many everyday sources generate charge below this level, and also do not do so on a steady current basis.

The rate of electrostatic charge generation is affected by many factors. Some of the key ones are:

Separation of the materials in the triboelectric series

Rate of separation of contact area (high rates of movement).

Charge decay time constant

The resistance and capacitance in Figure 1 form an RC network that has a characteristic time constant τ:

$$\tau = RC$$

In the example, if the 1 mA charge current is suddenly halted at time t = 0, the voltage V on the capacitor decays as:

$$V = V_0 \exp\left[\frac{-t}{\tau}\right]$$

An electrostatic fieldmeter 'looking' at the material surface would measure this exponential decay of voltage. In practice, the time constant for a material is given by the product of its resistivity r and permittivity εoεr

$$\tau = \rho \varepsilon_0 \varepsilon_r$$

In ESD work, a different definition of 'time constant' is usually used in standard measurements, and the time for charge to reduce to one-tenth of its initial value is measured. This value is theoretically equal to 2.3τ. Any material that has a time constant greater than about 2s is considered an insulator2 . Polymers may have time constants of many tens or hundreds of seconds, or even days under clean dry conditions.

2 The actual definition varies with different ESD standards

In practice the simple model does not always correspond well with material behaviour. The charge decay curve may depart considerably from the ideal exponential. There are many reasons for this. One factor is that material resistivity can have a voltage dependence, becoming higher as the voltage reduces. The resistance-to-ground of a work surface measured at 100V, will typically give a lower value than if measured at 10V!3

3 A major component of the voltage dependence of the resistance measurement is that extra charge is injected by the voltage source, that can contribute to the conduction processes. Other factors may also come into play, especially in non-homogenous materials. At high resistances a time dependence is also found with an initially higher current flowing due to polarisation of the material and charge injection. This reduces until a quasi-constant current flows after some elapsed time for a given voltage.

The role of standards in ESD work

Electronics manufacture is an international business, and manufacturing companies all over the world need to successfully implement ESD prevention measures. This has led to the development of ESD prevention standards such as EN100015, EN61340-5-1, ANSI/ESD 20:20, JESD-625-A and MIL-STD-1686. These standards are in the process of being harmonised in a global IEC standard.

If a manufacturer complies with one of these standards, customers have an assurance that good ESD prevention practice is in place and the possibility of ESD related product reliability issues has been minimised.

Adherence to such standards also requires standard test methods for measurement of key parameters such as material resistivity and charge decay time constant.

International standards covering such matters facilitate international trade in the equipment and materials required for ESD prevention, as well as the electronic products which result from the manufacturing processes.

Insulators and conductors

As charge generation rates in static electricity are often fairly low, a leakage resistance R (Figure 1) may be significant even if it has, to an electronics engineer, a high value. A resistance of 106Ω could be considered quite conductive, and would reduce the electrostatic voltage in the example to 1V!

Conductors are easily maintained at a low voltage by connecting them to earth (ground). However, an insulator in electrostatic terms cannot be maintained at a low voltage by installing a ground connection. A material that has a time constant of more than 2s is usually considered insulating in ESD work.

There is no fundamental definition of insulators and conductors in electrostatics. In reality there is a continuum of material resistivity from highly conducting (low resistance) to highly insulating (very high resistance). The following table shows how the terms insulating, dissipative and conductive are broadly applied to material resistivity ranges in the EN61340-5-1 and EN100015 ESD standards. Care should be taken in using these terms, because they may be defined differently in different contexts.

Table 2: Resistance range definitions

Terminology	Resistivity ranges		
	EN 61340-5-1(1) Packaging surface resistance only (Ω) (2)	EN100015-1(1) Volume resistivity (Ωcm)	EN100015-1(1) Surface resistivity (Ω)
insulating	$>10^{11}$	$>10^{11}$	$>10^{12}$
dissipative	$>10^{5}–<10^{11}$	$10^{4}–10^{11}$	$10^{5}–10^{12}$
conductive	$>10^{2}–<10^{5}$	$10^{2}–10^{5}$	$10^{3}–10^{6}$

Notes:
(1) EN100015-1 has been superseded by EN61340-5-1 but is still in common usage

(2) EN61340-5-1 uses a concentric measurement electrode that gives values approximately 9 times less than EN100015 electrodes

NB. Other standards may use different definitions of the terms insulating, conductive and dissipative.

The effect of humidity

Moisture from the air forms a thin layer on the surface of many materials and can contribute to their apparent electrical conductivities. Some materials, especially natural materials such as paper, reduce by orders of magnitude in their resistivity as humidity increases from dry conditions.

A commonly used measure of air humidity is 'relative humidity', expressed as a percentage (%RH). (See box).

As material resistivities are increased under dry conditions, electrostatic charge build-up is often greatly enhanced. Some ESD materials use additives to attract moisture to a polymer surface and provide static dissipative behaviour. These materials may not work well at low humidities. As a rule of thumb, electrostatic activity is generally favoured by humidity less than about 30%RH.

The external atmospheric humidity in the UK varies daily with the weather, in a range from approximately 10%RH (cold and dry winter conditions) to 100%RH (fog). The atmospheric humidity has a large effect on materials in the dissipative and insulating ranges.

Air humidity is a strong function of temperature, and reduces as temperature increases for a given moisture content. If, as in winter, cold air is brought indoors and heated, very low humidity can result. Hence, ESD problems can be seasonal and occur often in winter. Even in a controlled humidity room, dry local microclimates can form where there are heat sources such as equipment, especially if air circulation is restricted.

A view of the effect of humidity on static electricity in daily life is given by the following typical voltages observed at different ambient humidities.

Relative humidity

If a closed container contains some water, the air above the water will contain water vapour. At any temperature in a closed system this vapour reaches a saturation vapour pressure. If the container is open, the saturation pressure may not be reached but at any point has a lesser vapour pressure.

Relative humidity (RH) is 100% times the ratio of the actual vapour pressure Pa to the saturation vapour pressure Ps

$$\%RH = \frac{P_a}{P_s} \times 100\%$$

The saturation pressure Ps increases dramatically with temperature. If a volume of air contains a fixed amount of water vapour, then the relative humidity decreases rapidly as the air is warmed. As a rule of thumb, relative humidity approximately halves for a 10°C rise in temperature. Thus outside air entering a building at 10°C and 50%RH would have a relative humidity around 25%RH after warming to 20°C by the heating system.

Table 3: The effect of humidity on typical electrostatic voltages

Action	**Voltage observed (V)**	
	@ 10–20% RH	@ 65–90% RH
Person walking across carpet	35 000	1 500
Person getting out of a car	> 10 000 V	
Person walking across vinyl floor	12 000	250
Person working at bench (not grounded)	6 000	100
Opening vinyl envelope to get documents	7 000	600
Picking up polythene bag from bench	20 000	1 200
Movement while sitting in chair, padded with polyurethane foam.	18 000	15 000
Data from DOD-HDBK-263 and http://www.jci.co.uk/Carseats1.html		

Charge, voltage and capacitance

Electronic engineers are familiar with capacitors as components. The voltage V across a capacitor (capacitance C) is related to the stored charge Q by;

$$CV = Q$$

Electronic engineers are used to thinking of capacitors as fixed value components. In electrostatics, any conductive object can be said to have a capacitance, it is just the relationship between the stored charge and the object’s voltage.

$$C = \frac{Q}{V}$$

Capacitance is a variable

In practice, this capacitance is not fixed, but is a variable that depends on the materials and nearby objects, and proximity to earth. Objects move around in daily life, and so their capacitance changes.

As an example we can consider the human body. It is, in electrostatic terms, a conductive object, being mainly composed of water. Even if we neglect the nearby objects and earth, the human body can be approximated as a sphere that has a similar surface area4 . Typically a 1m radius sphere gives a useful approximation, and has a 'free space' capacitance around 110pF.

4 The free space capacitance of a sphere is given by $4\pi\varepsilon_0 r$, where r is the radius and ε_0 is the permittivity of free space, 8.8×10^{-12} F/m

Nearby objects and earth increase this value. In fact the human feet, on the earth, approximate two parallel plate capacitors in parallel with the free space capacitance. Each capacitor is made up of two electrodes – the sole of the foot and the earth. These are separated by a layer of dielectric (the shoe sole, typically a polymer of relative permittivity ε_r around 2.5). Each foot capacitance varies from moment to moment as the feet are lifted and replaced on the ground during walking. Each foot capacitance can be modelled as a parallel plate capacitor, with plates of area A separated by a distance d and capacitance C given by;

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}$$

A change in capacitance results in a change in voltage

In general, if either the area A or the distance of separation d are changed then the capacitance will change. If the charge is held constant, increasing the capacitance will decrease the body voltage, and reducing capacitance will increase body voltage. Reducing capacitance can be achieved by reducing the area (e.g. standing on tip-toe) or increasing the separation distance (e.g. raising the foot from the floor).

When seated in a chair, the body generates charge on the clothes surfaces in contact with the chair. This forms a capacitance of large area and small distance between the charges (the two surfaces are in contact). On rising from the chair the person can take much of the separated charge with them. The capacitance between the body and the chair is rapidly reduced (separation is rapidly increased) and a high body voltage quickly results if the charge cannot dissipate to ground. It is common to feel a shock after rising from a chair or car seat – voltages over 10 kV have been measured on people after getting out of a car seat.

Capacitance of everyday objects

It can be useful to have an idea of the approximate capacitance of everyday objects, especially when estimating the possible severity of electrostatic discharges from such items. Table 2 gives some examples.

Table 4: Capacitance of typical everyday objects

Electronic components & small assemblies	1 to 10 pF
Drinks can, small metal parts	10 to 20 pF
Small containers (1 to 50 litre)	10 to 100 pF
Larger containers (250 litres to 500 litres)	50 to 300 pF
Human body	100 to 300 pF
Large metal plant closely surrounded by earthed structure	100 to 1000 pF
Cars	800 to 1200 pF

If we consider the behaviour of a conductive object as a capacitor, we can quickly understand that the voltage on an isolated conductive object will change under the influence of a nearby charged object and its electric field.

Figure 2: Voltage developed on a metal object in an electric field

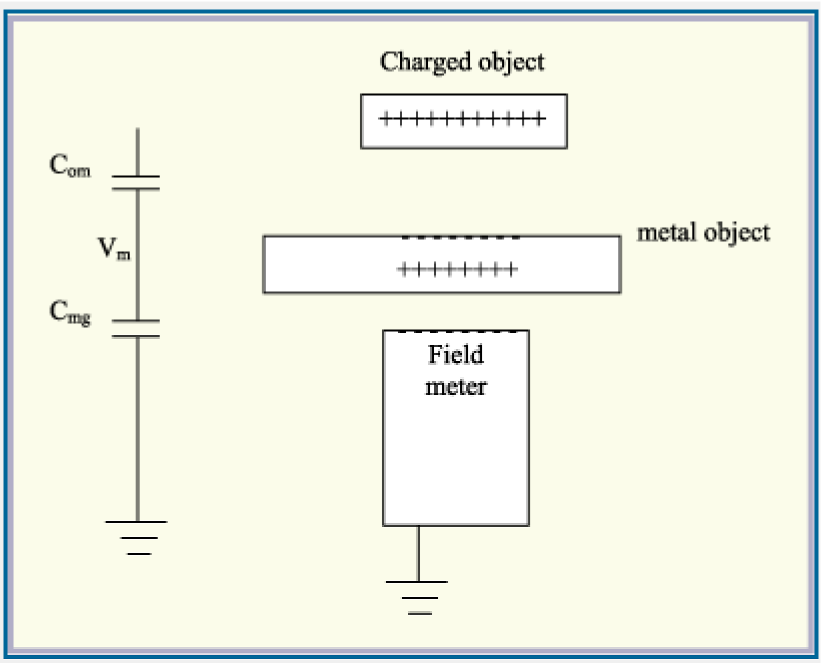

Figure 2: Voltage developed on a metal object in an electric field

In Figure 2 an earthed electrostatic field meter is monitoring the voltage Vm of a metal plate. There is an effective capacitance Cmg (fixed, as the test arrangement is fixed) between the metal object and the field meter. The metal object has no net charge and is initially at zero volts.

A positively charged object is then brought near. As it approaches it couples to an increasing amount of negative charge Q on the metal object. The same amount of positive charge appears on the side of the metal object nearest the field meter, coupled to an equivalent charge on the (grounded) fieldmeter. The voltage on the metal object increases (the capacitor Cmg is charged) by an amount

$$V_m = \frac{Q}{C_{mg}}$$

This can happen in practice if a conductive object passes through an electric field. If, for example, an integrated circuit passed into an electric field, it could acquire a voltage in this way. If it were subsequently grounded in this state, an ESD event could happen.

Charge can be induced on an object by grounding it

In the experiment of Figure 2, we saw that a voltage was induced on the metal object when a charged object was brought nearby. In that situation, we can discharge the capacitor Cmg by connecting a ground wire between the metal object and earth. The positive charges on the metal object flow to neutralise the negative charges on the fieldmeter. The voltage Vm is then zero. (Figure 3)

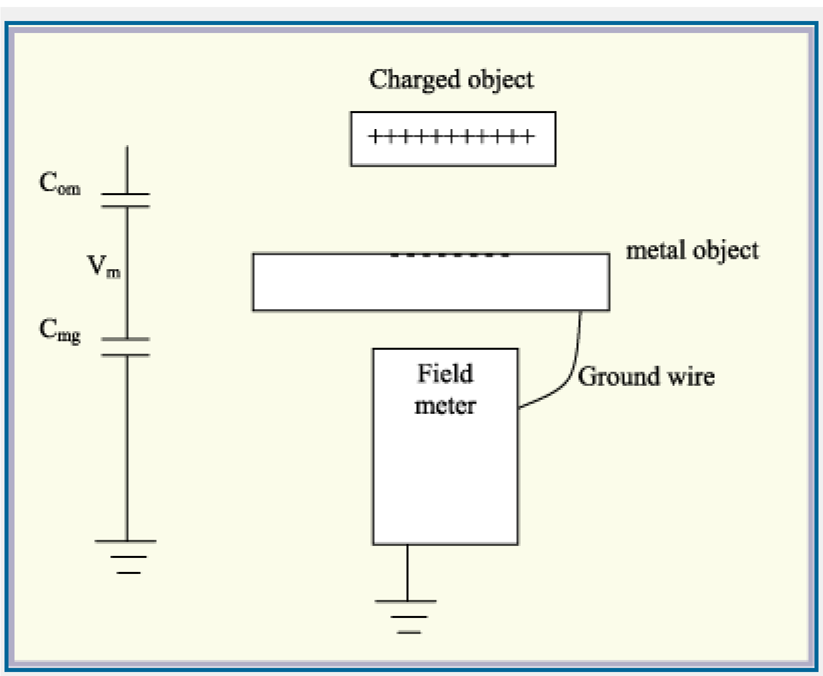

Figure 3: An earthed metal object in an electric field becomes charged by grounding

If the earth wire is then removed, the metal object remains at zero volts. However, it has a net negative charge Q. If the charged object is taken away, the voltage on the metal object rises due to its negative charge. It reaches a negative voltage

$$V_m = \frac{-Q}{C_{mg}}$$

This is called charging by induction. It can happen in practice if an object, tool, device or person becomes grounded temporarily when in an electrostatic field.

Electrostatic discharges

If the electrostatic field strength exceeds about 3MV/m (3kV/mm) the insulating properties of air break down and an electrostatic discharge occurs. A large amount of stored charge can be rapidly dissipated by this event. The discharge may be sudden, as in sparks, or it may be gradual as in corona discharge.

Corona discharge

Corona discharge is associated with conductors with sharp points or edges. The discharge arises as the electric field locally at the sharp surface is very high and above the breakdown field. Charge is 'sprayed' out from the electrode. The discharge can occur from a sharp point on a charged object, or can occur on a sharp grounded point in the field of a highly charged object. The discharge current is long duration and relatively steady at low current levels, typically <1mA. The power dissipation is low but high energies can be dissipated over a long period of time.

Corona discharges are one of the main means of producing ions used to neutralise electrostatic charge in ionisers in ESD work. In this case positive and negative high voltage corona sources are used to produce a balanced bipolar ion source.

ESD from insulating surfaces

A brush discharge can occur from a charged insulating surface to an approaching conductive electrode, when the electrode radius is not too small (>5mm). A number of contributory discharges occur on the insulating surface, radiating from a central spark channel – the whole looks rather like an old-fashioned twig brush.

Brush discharges are less well documented than spark discharges. They typically have an intermediate peak discharge current (0.01–10A) and unidirectional waveforms with fast rise and exponential decay. Power dissipation is intermediate power dissipation, and intermediate energies (estimated <10mJ) are dissipated over 0.01–1ms. Discharges from positive and negatively charged surfaces show distinct differences.

ESD (sparks) between conducting objects

The spark discharge occurs between conducting electrodes that initially have a high voltage difference between them. Large energies (mJ to >1J) may be dissipated in very short, or long, times (ns to >ms) depending on discharge circuit. Peak currents are typically greater than about 0.1A and can exceed 100A. The discharge waveform is highly dependent on the source and 'load' circuit characteristics and can have unidirectional or oscillatory waveforms.

ESD from the human body

The human body is a very important source of ESD, both in device damage in manufacturing processes, and in electromagnetic susceptibility of working systems. The body is a conductive object in electrostatic terms, and can have a variable capacitance up to about 500pF, although considerably higher capacitances have been measured under some circumstances.

Although the body is conductive, it has significant resistance, and this limits the current flow and causes human body ESD waveforms to have a characteristic unidirectional waveshape. The peak discharge current is typically in the range 0.1–10A with durations of around 100–200ns.

People perceive higher level ESD events as an electrostatic shock. Human sensitivity to ESD is rather variable, but the threshold of feeling ESD shocks is around 3–4kV for most people. ESD over 2–3kV may be heard, and higher level ESD over 5kV may be seen. Many lower level, but potentially damaging, ESD events can happen without the knowledge of the person concerned!

ESD from a charged human can also be sufficiently powerful to ignite flammable vapours.

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Source: http://www.ami.ac.uk/courses/topics/0214_ee/index.html