Is atmospheric plasma potential-free?

This article deals with the question of how to estimate whether certain electronic assemblies sensitive to electrostatic discharge effects (ESDs) can safely be treated with atmospheric plasma

Introduction

Atmospheric plasma treatment is a widely used and established method of fine cleaning and surface activation. For polymeres and composite materials, this activation via atmospheric pressure plasma will often be the most efficient and cost-effective method, while at the same time being compatible with virtually every series production process.

It is not necessary to use wet-chemical primers, which makes atmospheric plasma functionalization extremely environmentally friendly and gentle to materials. Fine cleaning, functionalization and static charge compensation can be achieved in only one single process step.

This is also true for the treatment of complete electronic assemblies. A circuit board, for example, assembles a wide variety of materials: thermoplastics, metals, ceramic surfaces, solder masks, conductor tracks and PCB substrate material. If this kind of component or module is supposed to be encapsulated, dry atmospheric plasma treatment optimization is a highly efficient method to achieve a homogeneous cast. Blowholes and cracks are avoided, moisture absorption is minimized.

In microelectronics, the underfill process is an example of synthetic resin coating. For flip-chip-mounting, the chip is soldered to have its active contact pattern face the circuit board directly. This makes for a very compact casing and reduced conductor length. For stabilization and improved thermal conduction, an elastic, heat resistant synthetic resin, the so-called “underfill“, is injected into the gap between chip and circuit board.

Typically, the underfill is dispensed next to the chip and fills up the gap due to the capillary effect. The quality and speed of this process are determined by the viscosity and wettability of the synthetic resin. Pretreatment with atmospheric plasma greatly enhances the flow velocity while at the same time optimizing the quality of the bonding.

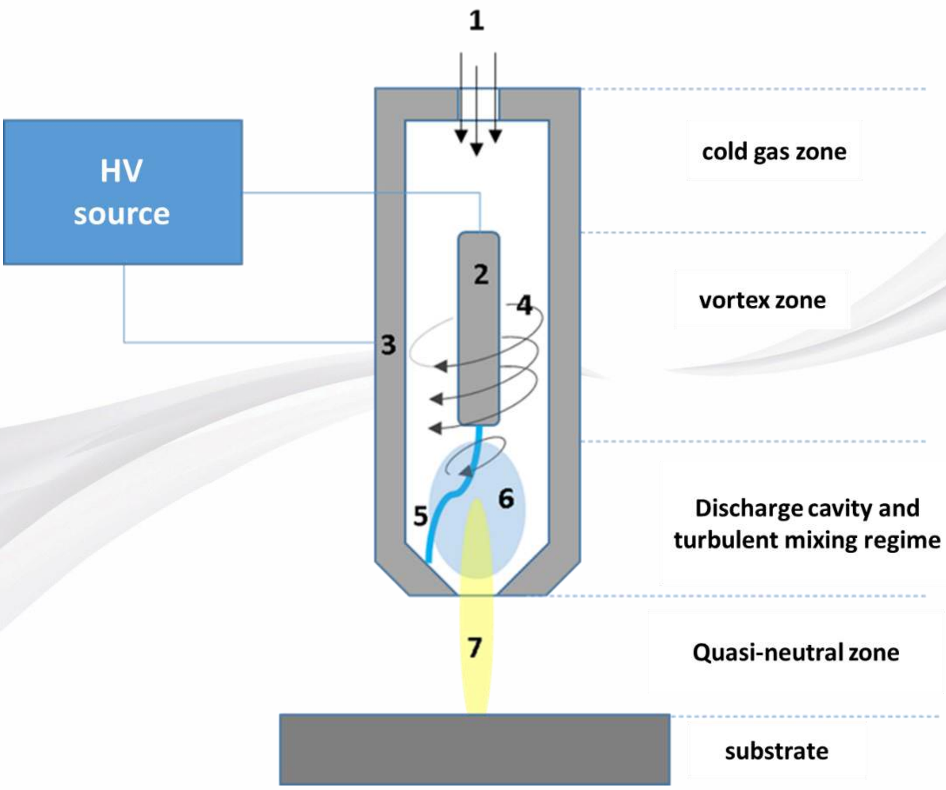
This article assesses the risks of damaging components during atmospheric plasma processes. For components or assemblies sensitive to electrostatic charging, we evaluate whether electric charge transfer is sufficiently suppressed.

Atmospheric plasma jets with vortex stabilized discharge flow

Typically, a highly reactive plasma jet is generated using air under atmospheric pressure. This method is successful when the concentrated jet, which emitted from the hot discharge zone, contains all surface-active species and ideally is electrically neutral in sum.

The nozzle-shaped plasma generators made by relyon plasma are especially compact and particularly stable in the long term. By using a high-voltage energy source with unipolar pulses and a vortex flow inside the nozzle, the electric arc is prevented from stabilizing at a “hot spot“.

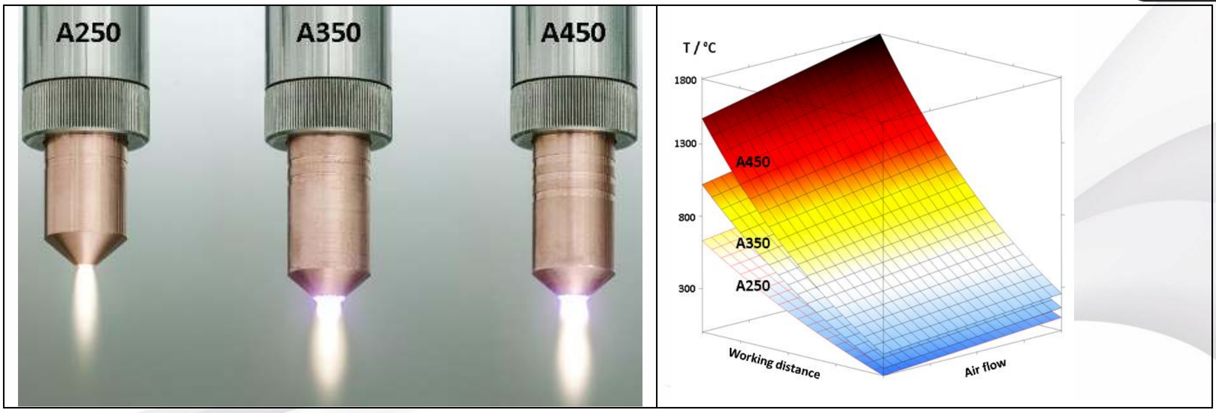
The electric arc rotates inside the discharge chamber at a high frequency. In spite of the high power density, the nozzle warms only slightly and the electrodes hardly erode at all, while the temperature of the plasma itself can be freely adjusted to a wide degree. This principle is illustrated below.



Picture 1: Schematic structure of an atmospheric plasma nozzle with external high-voltage source, an internal anode and a cathode placed on an ingot. At the gas inlet (1), the process gas (e. g. air) is supplied and directed into a vortex flow (4). Between anode (2) and cathode (3), a discharge ignites (5) producing a hot primary volume (6), which is then emitted as a jet (7) through the nozzle opening and onto the substrate.

Chosen Plasma System

Picture 2 High-voltage, unipolar pulse power source PS2000 with high-voltage cable and plasma generator



Picture 3: Replaceable nozzle series in order of increased power density and correspondingly higher static temperature. The A250 nozzle is optimized for low charge transfer, the A450 nozzle for maximum power density.

For this article, two different nozzle types have been chosen to illustrate the implications of this factor. Both nozzles are operated in PAA® mode and compared. The A450 nozzle is optimized for high power density and clearly shows two zones within the plasma flame. The A250 nozzle is optimized for low charge emission.

Plasma treatment has a thermal, chemical and electrical effect on the surface in question. The effect depends on the settings of the process parameters, such as working distance, the type of process gas used, the settings for excitation power and speed of operation as well as the characteristics of the substrate. The thermal effects have already been analyzed in a separate article (Nettesheim, Korzec & Burger, 2015). The following article will focus on electric charge transfer and its effects on sensitive components or assemblies.

Mechanisms of charge transfer

Direct charge transfer

During atmospheric plasma treatment, strong electric fields build up between anode and cathode. However, the secondary plasma which is emitted is electrically neutral in sum and its effects on the surface are achieved more through the activation of chemical species that through field effects on the surface itself (in contrast to a corona discharge). Despite this, reservations are often expressed that sensitive components might be damaged by inadmissible potentials.

For atmospheric plasmas where pulsed electric arcs are ignited, the electron temperature of the core filaments can reach 10,000K, while the medium temperature of the heavy neutral particles and ions can amount to less than 1000K. This temperature rapidly sinks due to expansion, radiation loss and turbulent mixing at the nozzle exit. Inside the discharge chamber near the hot core, particle density for charged particles is up to 10^{13}/cm3. In this phase, charge disequilibria occur on a length scale defined by the Debye length (Liebermann & Lichtenberg, 2005).

$$\lambda_\mathrm{D} \approx \lambda_\mathrm{De} = \sqrt{\frac{\varepsilon_0\, k_\mathrm{B} T_e}{n_e\, e^2}}$$

For an assumed electron temperature of 10,000K and a density of $10^{13}/\mathrm{cm}^3$, the resulting length is < 0,2mm.

Only within this short length, potential differences are observed which are no longer shielded immediately by charge movement and therefore, under certain conditions, might be carried along with the plasma flow to the nozzle exit or to a sensitive substrate.

Fluctuations within the free charge carrier density

The charge carrier density in the plasma jet will fluctuate if arc intensity is pulsed or stochastically oscillating. The frequency spectrum of this fluctuation is typically between 20 and 100 kHz for pulsed arc discharge. The discharge velocity at the nozzle is around 50m/s and therefore, charge carrier intensity can be expected to fluctuate on a length scale of ca. 1mm. Additional fluctuations are induced by the turbulent regime of the discharge. The sum of all these fluctuations is transferred to the charge carrier density and therefore to the conductivity of the emitted plasma jet. However, the fluctuations will average themselves out on the way between the nozzle exit and the substrate, given that this distance is substantially longer than the length scale of the fluctuations.

Inductive (magnetic) coupling

This article completely ignores magnetic or inductive energy coupling into conductive structures on a substrate because magnetic field strengths can be neglected due to the low currents (< 1A) and the relatively large distance of >20mm between the current loop in the discharge zone and the substrate.

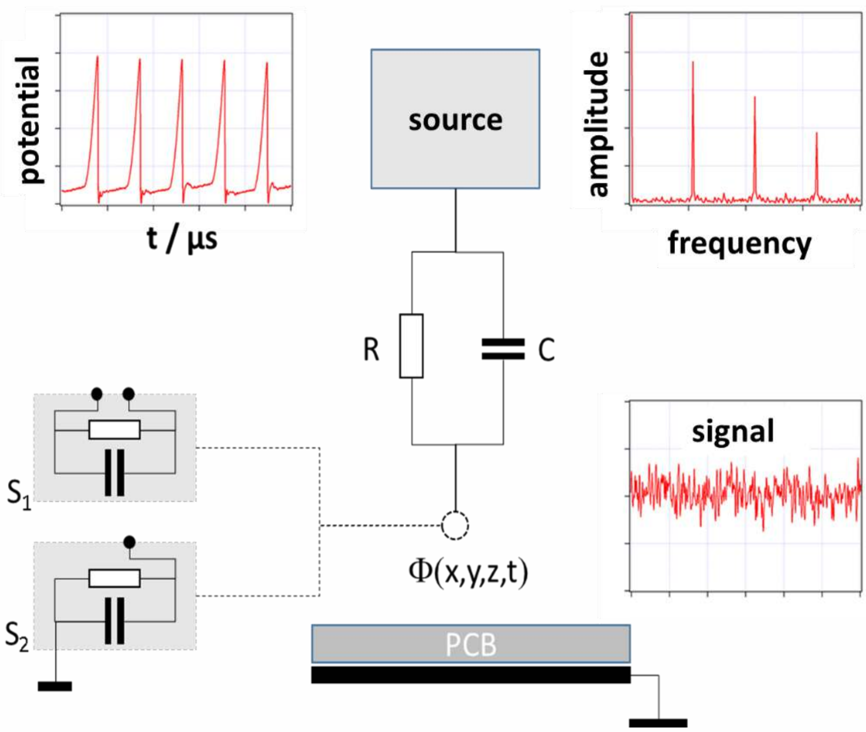
High-frequency electromagnetic coupling

High-frequency electromagnet fields can only be efficiently transmitted from a sender to a receiver if the antenna structures lie within the scale of the electromagnetic wavelength. Inside the plasma generator and on the substrates, these lengths are within the range of a few centimeters. The power spectrum in the near field of the plasma nozzle shows frequencies of only about 100kHz, corresponding to wavelengths of ca. 3000m with a relevant amplitude. In order to transmit these frequencies effectively, very large antenna structures would be necessary. Therefore, openings which are much shorter than the wavelength will not be permeated.

Capacitive (electric) coupling

In addition to direct charge coupling, capacitive AC decoupling through the nozzle exit is also thinkable. Due to the partially stochastic nature of the atmospheric discharge between two electrodes, high-frequency transients occur on the internal anode. (cf. picture 1).

Test setup and execution



Picture 4 Measuring principle and equivalent circuit diagram. The power source is characterized by its amplitude, frequency and pulse shape, depicted as required either as a pulse train or as an amplitude spectrum in the frequency domain. Measuring of potentials is either carried out using a differential probe S1 or a simple probe S2.

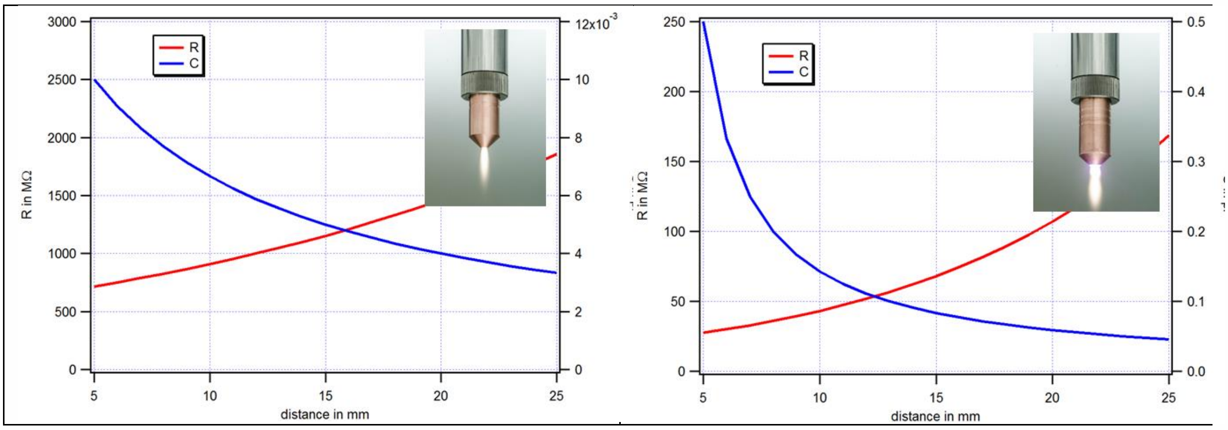
Naturally, the local electric potential measured depends on the chosen test setup and it is therefore crucial to clearly characterize the probe used for measuring in order to examine the precise load of the component later. In principle, there is a conductive connection in the space between the internal electrode on working voltage through the nozzle exit and to the substrate (e. g. a circuit board). A plasma contains free movable charge carriers.

The measured result will be defined by the internal resistance and the capacity of the probe used as well as the bandwidth of the recorded frequency spectrum. For practical interpretation, an additional distinction can be made between an absolute local potential and a local potential difference which builds up between two probes spaced apart (differential measuring S1, measuring referring to mass S2).

We used a storage oscilloscope (Tektronix) and a high-quality detector head (10MOhm, 8pf) to perform a spatially resolved measurement of the absolute and the differential voltage signal and we did a spectral analysis for each setup.

Discontinuing the plasma flame using a dielectric plate made of Al_2O_3 will decrease the DC proportion of the measurement signal but will hardly alter its AC proportion. The operating frequency of the pulsed high-voltage source continues to be visible in the power spectrum. This means that even when the substrate is completely insulated from the plasma source, an electrical power is capacitively transmitted which can put stress on the component.

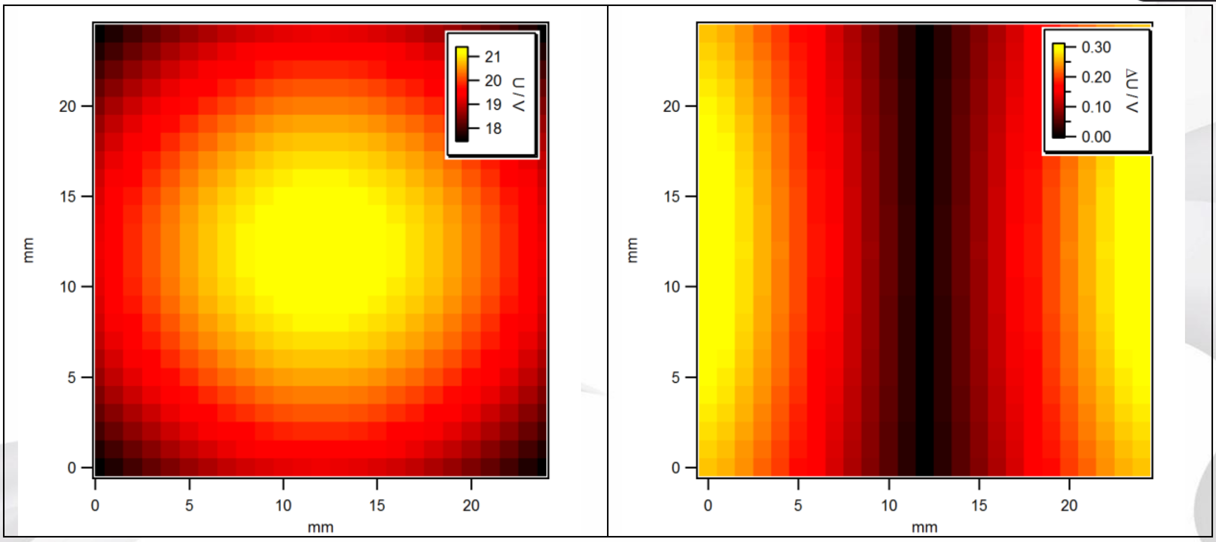
From these measurements, values can be deducted for the RC element used as the assumed equivalent circuit at any given excitation voltage.



Picture 5 Location dependency of the RC parameter, which describes the charge transfer of the plasma jet and can be calculated from the measurements.

The tendency described above is intuitively plausible: with growing distance, the capacity forming between the plasma nozzle exit and the measuring probe's surface will diminish while simultaneously, free charge carriers in the secondary plasma jet recombine and the plasma flame cools. Thus, electrical resistance rapidly rises with increased distance.

For a typical operating process with our low-potential nozzle A250 and a working distance of 20mm, the location-dependent potential was measured with a sensor at 100MOhm referring to mass (cf. picture 6, left) and at 100MOhm differentially (cf. picture 6, right). For the differential measurement, the distance between the measuring points was 1mm. Picture 6 shows the location-dependent potential for an area of 25x25mm^2. The maximum difference in potential for the entire area was approx. 3V, while local differences in potential were less than 300mV when measured with a differential probe.



Picture 6 Location-dependent potential, measured with a sensor at 100MOhm against ground (left) and at 100MOhm differentially between two measuring points in horizontal line contested by 1mm (right).

Applied model system

A simple CMOS gate (complementary metal-oxide-semiconductor) serves as a model system, as most digital ICs (sensors, processors, working storages) are currently produced using this technology. For typical structural dimensions of less than 1µm, breakdown voltages are below 20V.

Power dissipation in idle mode is usually about 10nW. Dynamically, each gate uses about 10µW-100µW/MHz, which means that a single element shows input impedances of ca. 1GOhm and typical capacities of ca. 1pF. CMOS interfaces are sensitive to static charges and overvoltage, which is why one- or two-stage protective circuits are placed in front of them where technically possible, for example in the form of diodes against both operating voltages. Typically, this reduces pin to pin resistance for an integrated component to <100MOhm.

In practice, individual gates are connected to form logical structures, which are packaged and soldered onto the circuit board, with structures, e.g. bond wires, being within a millimeter range. The specific issue therefore is whether the plasma flame can induce a potential difference over a distance of a few millimeters which might then break the barrier layer on a discrete CMOS gate. For this, a simple probe can be defined to perform practical measurements.

Conclusion

Direct charge transfer can be kept minimal in atmospheric plasma processes, provided the substrate is not placed immediately near the hot zone and the nozzle type used ensures good confinement of the primary discharge zone. Thus, damage can be ruled out even for very sensitive components such as CMOS gates.

A good understanding of the working process and the plasma system used is important for making an informed assessment. Even without a detailed case-by-case examination, a simple equivalent circuit diagram for the plasma flame makes it possible to evaluate potential risks posed by charging effects..

Literature

Liebermann, M. A., & Lichtenberg, A. (2005). *Principles of Discharges and Materials Processing.* New Jersey: Wiley.

Nettesheim, S., Korzec, D., & Burger, D. (2015). Plasmaaktivierung von Rolle. *Adhäsion*, 20-25.