Characteristics of Atmospheric Pressure Corona Torch Plasmas for Material Processing

J. Markle, C.Q. Xu and J.S. Chang

Dept. of Engineering Physics, McMaster University, Hamilton, ON L8S 4L7, Canada

Characteristics of corona torch plasmas with a configuration of torch-ferroelectric material-metal were studied. The ion density distribution downstream from the corona torch exit was measured using a floating potential double probe. Ion density at the exit of corona torch is order of magnitude of 10E+12/cc. Optical spectroscopy revealed that the discharge consisted mainly of the second positive band of nitrogen and the vibrational temperature was observed to be 3953 K. For the material processing such as domain inversion of ferroelectric materials (Poling).The corona torch may be operated above these materials. The ferroelectric material contributes time dependence to the poling process and significantly influences the discharge characteristics of the corona torch. Unlike corona torch treatment of insulating materials, the ferroelectric material and the discharge are linked to the extent that the corona poling may be a self-terminating process.

1. Introduction

Corona discharge is a relatively low power electrical discharge that takes place at or near atmospheric pressure. The form of the discharge is dependent on polarity and electrode configuration. One common material processing function of corona discharge is to treat low surface energy polymers. This method is used for rendering the surfaces more receptive to adhesives and decorative coatings by subjecting them to a high voltage corona discharge. The corona discharge oxidizes the surface through the formation of polar groups on reactive sites making the surface receptive to coatings. Another material processing function of corona discharge is the poling of polymers and ferroelectric materials [1]. These materials can be manipulated by the presence of large electric fields. These fields are a result of negative charge accumulated on the sample surface and a grounded metallic electrode below.

In corona based ferroelectric material processing such as crystal poling, a uniform electric field provided by stable surface charges is required [1]. The use of the flow stabilized discharge corona torch [2-3] is able to ensure adequate surface charge for initiation of the domain inversion process. The corona torch had many variable parameters such as the size of grounding ring, position of grounding ring, extension distance of discharge tube, etc., so that greater control can be achieved.

In order to measure the ion density distribution downstream from the corona torch exit, a floating double probe [5] was used under continuum plasma conditions [4]. Electrostatic probes are simple devices; however, depending on the plasma environment a suitable theory is required for analyses. Electrostatic probes have the advantage for local measurements where spectroscopy and the other methods measure over integrated large plasma volumes.

In order to better understand the nature of the discharge used in the poling process, the optical emission spectrum was measured for determination of the vibrational temperature and the species of excited nitrogen molecules present in a plasma. Emission spectroscopy is a non-disturbing method used to investigate plasma parameters such as the identification of molecules, vibrational and rotational temperatures, electron and ion densities, etc.

2. Experimental

The corona torch was suspended inside an 8 liter Pyrex glass environmental chamber. The environmental chamber was filled with nitrogen gas which allowed for greater control and reproducibility of discharge and material processing parameters. Figure 1 shows a schematic of the experimental apparatus.

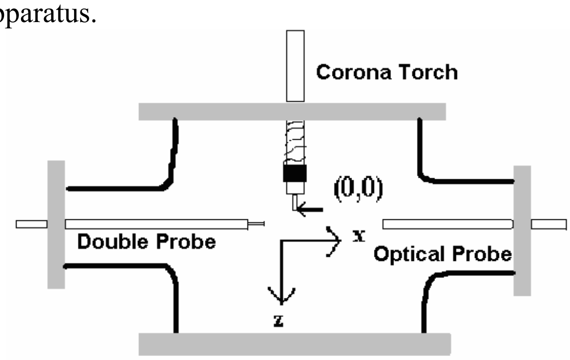

Fig. 1 Schematic diagram of the experimental apparatus with double probe and optical sensor

The corona torch was translated in a 12.7 mm (1/2") Cajon fitting positioned in the center of the top flange of the environmental chamber. This type of connection allowed for variability of corona torch position in the z-direction. The high voltage is insulated from the grounded flange by a (12.7 mm OD by 6.35 mm ID) Teflon tube. Inside the Teflon tube the stainless steel tube is stepped down in diameter. Figure 2 shows a schematic of the corona torch.

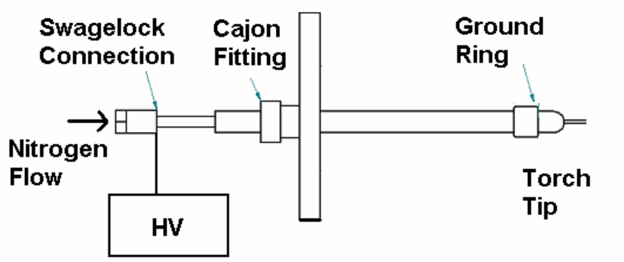

Fig. 2 Schematic of corona torch. HV: high voltage power supply.

The double probe was positioned in different locations downstream of the corona torch tip in order to measure the ion density distribution. Most electrostatic probes function by varying the probe voltage with respect to a known reference and analyzing the I-V characteristics. The problem with employing a probe of this nature is that it requires a steady state plasma discharge and will disturb the plasma environments. The double probe method was originally proposed by Johnson and Malter [5]. This device was developed to measure afterglow plasmas, in which the plasma potential changed with time, so that it was difficult to maintain a constant probe-plasma potential difference. With two probes biased with respect to each other but insulated from ground, the entire system "floats" with the plasma and therefore follows the change in plasma potential [5]. This device functions by providing a DC electric potential between two small wires biased with respect to each other and insulated from ground. The double probe is immersed in a plasma region and current flows between the two probes. The current flow through the double probe is proportional to the ion density [5], where continuum double probe theory was used for the plasma density determination [4].

An optical fiber with a focusing lens was positioned in close proximity to the corona discharge. The spectrometer used was a USB4000 Miniature Fiber Optic Spectrometer by Ocean Optics. The spectral range is 200-850 nm with a resolution of 0.3 nm.

During a corona discharge in nitrogen, the molecules are transferred into the excited or ionic state by collision with energetic electrons. After that, the excited and ionized molecules transit into a lower energy state by emitting radiation of a specific wavelength. The resulting spectroscopy yields information about the electron energy and density.

The nitrogen molecule can be transferred from the lower energy state $(X^1\Sigma_g^+)$ into the excited state $(C^3\Pi_u)$ by the impact of electrons with energy greater than *11 eV*. In the radiative emission process the $(C^3\Pi_u)$ electrons will transfer into the $(B^3\Pi_g)$ state by emitting a photon with a wavelength of 337.1 nm.

In general, the band intensity is given as [7]

$$I_{v'v''} \propto N_{v'} A_{v'v''} \upsilon^4_{v'v''} \tag{1}$$

,where $I_{v'v''}$ is the band intensity for a transition between vibrational energy levels $E_{v'}$ and $E_{v''}$ of the nitrogen molecule $C^3\Pi_u(v')$ and $B^3\Pi_g(v'')$ states, $N_{v'}$ is the population density of the vibrational energy level $E_{v'}$, $A_{v'v''}$ is the Frank Condon factor associated with the v'-v'' transition and $V_{v'v''}$ is the transition frequency. The population density of the vibrational energy level can be calculated from the measured band intensities $I_{v'v''}$ using equations 2 and 3. Both the Frank-Condon factor and the transition frequency are known values [6,7].

$$N_{v'} \propto \frac{I_{v'v''}}{A_{v'v''} \upsilon^4_{v'v''}} \tag{2}$$

In equation 3 [7], N_π is the total population of $C^3\Pi_u$ state, Q is the vibrational partition function, K is Boltzmann's constant and $T_{v'}$ is the vibrational temperature.

$$N_{v'} = \frac{N_\pi}{Q} \exp\left(-\frac{E_{v'}}{kT_{v'}} \right) \tag{3}$$

The relative population density $N_{v'}$, can be determined experimentally by plotting the population density versus the vibrational quantum number v' on a semi-logarithmic plot and measuring the slope. Ideally, the points should all lie on a straight line meaning the population density distribution follows a Maxwellian distribution.

3. Discharge Characteristics

The corona torch performance is dependent on the various parameters. Some of the critical variables are: applied voltage, position relative to charging surface, grounding electrode scheme, gas used, flow rate, etc. The ideal discharge yields a uniform glow on the surface in the desired poling region. The corona current waveform of such a discharge is roughly stable and diminishes as poling progresses and surface charge increases. The corona current is the current involved in the plasma discharge and is measured by the high voltage amplifier. Figure 3 shows the time average discharge current for various voltages and discharge configurations.

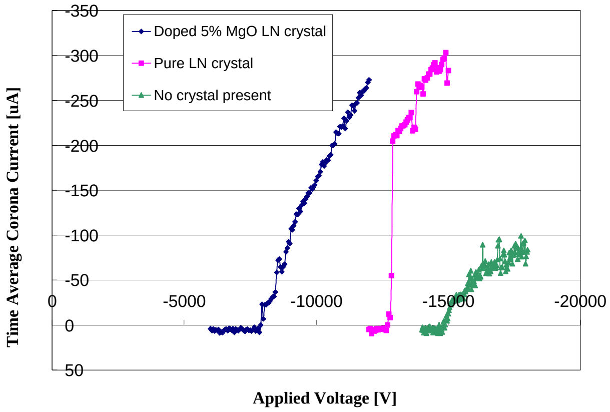

Fig. 3 Time average discharge current-voltage characteristics

One important variable in the poling process is related to the crystal. The presence of the grounded crystal and the crystal doping significantly influence the discharge characteristics. The influence of the different corona torch parameters were originally studied without the crystal present. The crystal positioned downstream from the corona torch functions like a ground surface, which drastically changes the discharge characteristics. The corona onset voltage of the corona torch without the crystal positioned beneath is roughly -15kV. The maximum achievable currents are much lower before the initiation of sparking in the case without the crystal present .

The crystal doping also has a significant effect on the corona torch characteristics. The 5% MgO doped crystal compared to the pure lithium niobate crystal has a much higher conductivity. This conductivity is due to the reduction of Li vacancies which function as traps for electrons in the conduction band. Figure 3 shows the effect of crystal presence on corona torch discharge characteristics at flow rate of 4 L/min, where the crystal was placed 15 mm in front of corona torch. The corona on-set voltage becomes lower when the crystal is present and the conductivity of the doped crystal also helps to reduce corona on-set voltage.

4. Plasma Characteristics

Using the electrostatic double probe the ion density distribution was measured. Figure 4 shows a schematic of double probe ion density profile. The corona torch was set to a constant discharge voltage 17.7 kV and nitrogen flow rate of 3 L/min. The ground ring was fixed at 30 mm above the edge of the corona torch hollow electrode which drove the torch with a nearly constant current of 150 μA. It was observed that the position of the ground ring influenced the corona current but did not significantly alter the relative ion density distribution.

The gas flow rate of the corona torch was not observed to influence the distribution of the ion density. The gas flow rate affected the magnitude of the corona torch discharge current and its waveform only at flow rates below 2 L/min. For this reason, the ion density and distribution was studied at 2 L/min. Figure 4 shows the ion density profile below the gas flow exit of the corona torch. From Figure 4 it is clear that the ion density decreases with increasing distance from the corona torch gas exit.

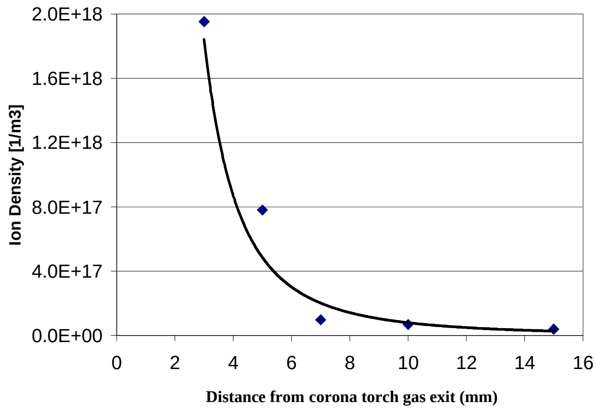

Fig. 4 Axial plasma density profile down stream of a corona torch exit (=0).

Figure 5 shows the ion density distribution contour lines downstream of the corona torch. Figure 5 shows that the radial distribution of ion density becomes more uniform as the axial z-direction distance is increased. This suggests that greater process uniformity may be achieved by increasing the spacing between the corona torch and the lithium niobate crystal. Ion density at
The corona torch exist is the order of magnitude of 10E+12/cc and hence relatively denseplasma can be generated.

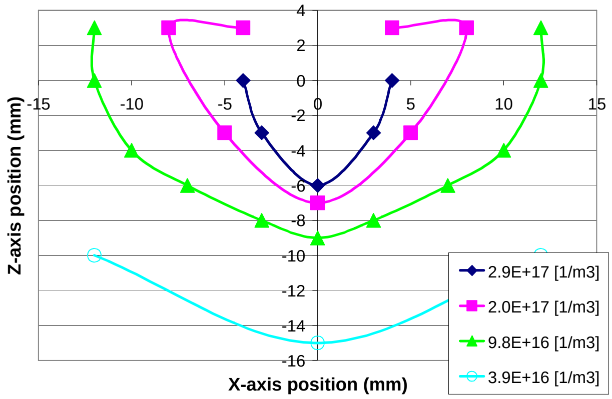

Fig. 5 Plasma density profile

Figure 6 shows a typical optical emission spectrum of the corona torch. Figure 6 shows that the observed spectrum consists mainly of the second positive band (PB) of nitrogen. The vibrational temperature calculated from the N_2 spectrum in Figure 6 was 3953 K.

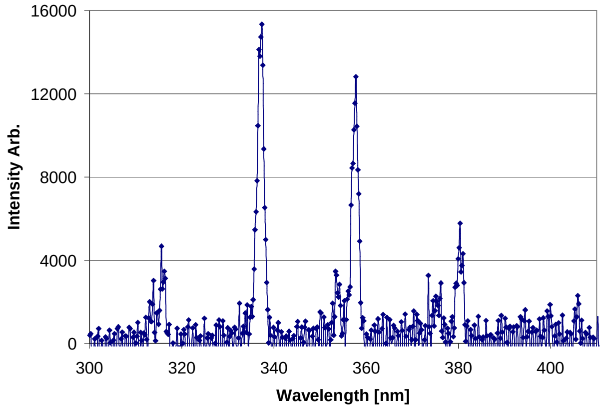

Fig. 6 Typical optical emission

5. Concluding remarks

Characteristics of corona torch plasmas with a configuration of torch-ferroelectric material-metal have been studied in detail. It has been found that by soft charging the (-z) surface of the crystal via a negative polarity corona discharge, a more uniform process of domain inversion can be achieved. Through this soft charging method the negative effect of crystal irregularities can be minimized by limiting the mobility of charge. The crystal contributes time dependence to the poling process and significantly influences the discharge characteristics of the corona torch. The crystal and the discharge are linked to the extent that the corona poling is a self-terminating process.

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6. References

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