Electrical and Spectroscopic Investigations on Atmospheric Pressure Dielectric Barrier Discharge Plasma

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Abstract

- Experiments have been performed to characterize self-designed parallel-plate DBD plasma source operated at atmospheric pressure in helium gas.
- The discharge was ignited with high voltage (2-5 kV) sinusoidal voltage of 1-20 kHz frequency. The discharge was observed to remain stable & uniform in our parametric range.
- Measured discharge current waveforms show one peak per half cycle that indicates non-equilibrium diffused nature of the discharge.
- Electron density and temperature were measured using spectroscopic He-I line intensity ratio method based on collisional-radiative (CR) model code.
- The electron density was obtained \( \sim 2 \times 10^{11} \, \text{cm}^{-3} \) while electron temperature was \( \sim 3-8 \, \text{eV} \) that are typical values for laboratory glow discharges.
- Parallel-plate discharge characteristics were obtained through optical imaging and electrical measurements.
- Further we have also found that selection of operating frequency and dielectric material are very crucial for getting discharge stability in DBD plasma.
Dielectric Barrier Discharge (DBD)

- The dielectric barrier discharges are low-current AC glow discharge plasmas that are operated near/at atmospheric pressure. The dielectric covered electrodes, high AC voltage, kHz range frequency, flowing inert gas etc. are generally required to produce stable DBD plasma.
- The possible modes are filamentary discharge or uniform discharge depending on operating parameters.
- DBD can be produced in a variety of electrode geometries (such as parallel-plate, coaxial, planar) and in many gases (such as He, Ne, N₂, Air).
- Uniform DBD plasmas are possible in a large-scale without requirement of any vacuum system. Hence they are exploited for various industrial applications. The popular applications include Ozone synthesis, Surface processing, UV lamps, Plasma Display panel, Pollution control, Biomedical applications, Aerospace applications and Plasma Stealth etc.

**DBD Phenomenon**

- Positive half cycle of applied voltage
- Negative half cycle of applied voltage
- Discharge initiation
- Discharge extinction
Distribution of Applied voltage in dielectric barrier discharge

\[ V_g(t) = V_a(t) - V_m(t). \]

\[ V_m(t) = \frac{1}{C_d} \int_{t_0}^{t} I(t) \, dt + V_m(t_0). \]

- \( V_a \) – Applied voltage
- \( V_g \) – Gas voltage
- \( V_m \) – Memory voltage
- \( I_d \) – Discharge current
- \( C_d \) – Dielectric capacitance

\( C_d = 470 \text{ pF} \)

\( V_m(t_0) = 851 \text{ V} \)

Common DBD Configurations

Parallel-plate electrodes
- Suitable Applications:
  - Basic studies/Plasma diagnostics
  - Material surface processing

Co-axial electrodes
- Suitable Applications:
  - Ozone synthesis
  - Biomedicine
  - Pollution control

Co-planar electrodes
- Suitable Applications:
  - Biomedicine
  - UV lamps
  - Plasma displays

Planar electrodes
- Suitable Applications:
  - Aerodynamics
  - Microwave absorption
  - Plasma displays
Dielectric layer Effect: Optimization of DBD cell capacitance

Estimation of Breakdown voltage
(Kim et al., Jpn. J. Appl. Phys, 37,L1549,1998)

\[ V_B = \frac{BP(d + 2t_d)}{C(\varepsilon_r)[\ln(APd/\ln\{1 + (1/\gamma)\})]} \]

\[ C(\varepsilon_r) = \frac{\varepsilon_r}{1 + (\varepsilon_r - 1)\{d/(d + 2t_d)\}} \]

Where,
- A, B : gas constants
- d : discharge gap
- \( t_d \) : dielectric thickness
- \( \varepsilon_r \) : dielectric constant

Effect of dielectric constant

Effect of dielectric thickness

Stabilization of DBD plasma

Parallel-plate electrodes (SS-304)

Applied voltage and Discharge current waveforms

Operating Parameters:
- Operating Pressure = 760 Torr
- Background gas = Helium, 99.999% pure
- Waveform = Sinusoidal
- Applied Voltage = 2-5 kV(p-p)
- Operating frequency = 10 kHz
- Discharge gap = 1-10 mm
- Dielectric = 150 micron thick Polypropylene sheet ($\varepsilon_r = 3.5$)

Discharge Current: 10-50 mA
Current Density: 1-5 mA/cm$^2$
Effect of Applied Frequency

Operating parameters:
- Pressure = 760 Torr
- Voltage = 2 kV (p-p)
- Frequency = 50 Hz
- Electrode gap = 5mm

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Roth's model

\[
\frac{eU_{\text{rms}}}{\pi m_i v_{ci} d^2} \leq \nu_0 \leq \frac{eU_{\text{rms}}}{\pi m_e v_{ced} d^2}
\]

Dielectric covered Electrodes
Filaments in the discharge

Dielectric covered Electrodes
Diffuse discharge

Graphs showing variation of applied voltage and current with time.
Electrical Measurements: Parallel-plate DBD Plasma

1. Variation of discharge gap (d)

2. Variation of applied voltage

3. Variation of frequency

- Discharge current

Power density vs. Applied voltage

**R. Roth’s model**

\[
\overline{P_d} = \frac{N_e \pi^2 V_{\text{rms}}^2}{8 m_e V_c d^2}
\]

Power density vs. frequency

**R. Roth’s model**

\[
\overline{P_d} = \frac{N_e \pi^4 m_e V_c d^2 V_0^2}{8}
\]
Optical Emission Spectroscopy

1. Wavelength calibration: Estimation of unknown wavelength

Selected Helium lines: 4922 Å, 5048 Å, 7065 Å, 7281 Å
2. Absolute intensity calibration: Tungsten ribbon source

Calibration set-up

[Image of calibration set-up with labels: Convex lens, Aperture, Filament, Tungsten Ribbon Calibration lamp, Optical fiber, Transmission glass window, Power supply leads.]

[Graphs showing intensity calibration factor vs. wavelength (Å).]
3. Line intensity ratio method based on collisional-radiative model (Fujimoto et al.)

**Spectroscopic Measurement of electron density**

4922 Å / 5048 Å

Intensity ratio ~ 2.0

\[ N_e \approx 1.3 \times 10^{11} \text{ cm}^{-3} \]

**Spectroscopic Measurement of electron temperature**

7281 Å / 7065 Å

Intensity ratio ~ 0.17

\[ T_e \approx 4.5 \text{ eV} \]
Measurements of Line Intensity Ratios
(Variation of applied voltage and frequency)
Electron density and Temperature
(Spectroscopic measurements)
Conclusions

- The uniform glow discharge at atmospheric pressure was produced using parallel-plate Dielectric Barrier Discharge (DBD) source in Helium gas.
- The discharge current waveform shows single dominant peak per half cycle of applied voltage to exhibit a diffused uniform discharge mode. The measured low discharge current density indicates that it is a non-equilibrium glow discharge plasma.
- The discharge transforms to filamentary mode as the frequency is reduced from 10 kHz to 50 Hz.
- We found that the breakdown voltage of DBD plasma was found to be reduced by selecting thinner dielectric layer with higher dielectric constant.
- Discharge power density was found to increase with applied voltage and frequency and follow power laws as suggested by Roth et al.
- Electron density and temperature were obtained through optical emission spectroscopy using He-I line intensity ratio method based on C-R model.
- The measured values of electron density and temperature are consistent with typical values as obtained for a laboratory glow discharge plasma.
- We finally conclude that DBD is a promising technique to produce atmospheric pressure glow discharge plasma. Such plasma sources can be scaled up for various industrial and societal applications.
REFERENCES


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Thank You