Observation of Self-excited Ionization Waves in a Planar Dielectric Barrier Discharge System at Atmospheric Pressure

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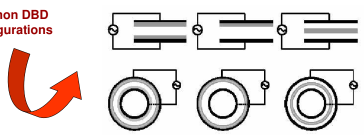
Abstract

- The glow discharge instability has been observed in the form of moving stripe pattern first time in a planar dielectric barrier discharge in helium gas at atmospheric pressure.
- This self-excited discharge instability has been analyzed in the form of low-frequency ionization wave of a glow discharge plasma.
- Increase of applied voltage increases the wave frequency. The coherent oscillation excited at low voltage becomes random & turbulent at high voltage and finally disappears to form a uniform atmospheric pressure glow discharge.
- The dispersion relation of these observed ionization wave was obtained and compared with the theoretical dispersion relation. A good consistency between experiment and theory was achieved.

Dielectric Barrier Discharge (DBD)

Common DBD Configurations



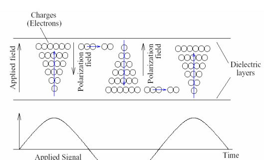
- The dielectric barrier discharges are low-current AC glow discharge plasmas that are operated near/at atmospheric pressure. The dielectric covered electrodes, high AC voltage, kHz range frequency, flowing inert gas etc. are generally required to produce stable DBD plasma [1, 3].
- The possible modes 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, N_2, 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

Aim: Discharge current limitation to prevent glow-to-arc transition.

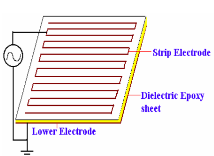
Positive half cycle:
Net field = Applied field - Pol. field
→ Discharge Extinction

Negative Half cycle:
Net field = Applied field + Pol. Field
→ Discharge Initiation

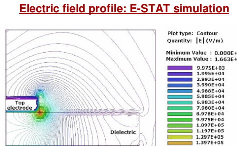


Characteristics of Planar DBD Plasma

Planar dielectric barrier discharges are produced over a planar flat surface making a sheet shaped plasma using specifically designed electrodes [1, 5, 7].



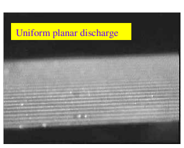
Electric field profile: E-STAT simulation



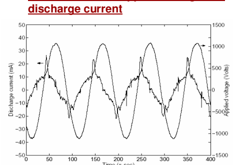
Stripe electrode material: Copper

Dielectric: Epoxy (permittivity: 3.2, thickness:2.2 mm)

Stripe masking: Polymeric liquid (green)



Time variation of applied voltage and discharge current

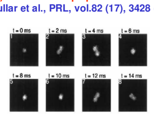


Striated DBD and Pattern formation: A survey

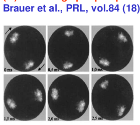
(i) Concentric ring pattern
Gurevich et al., PRL, vol.91 (15), 154501 (2003).

(ii) Stripe pattern
Breazeal et al., PRE, vol.52 (2),1503 (1995).

(iii) Dumbbell shape pattern
Mullar et al., PRL, vol.82 (17), 3428 (1999).



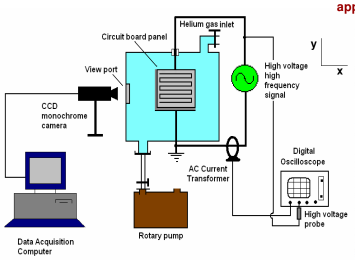
(iv) Travelling spot-pair pattern
Brauer et al., PRL, vol.84 (18), 4104 (2000).



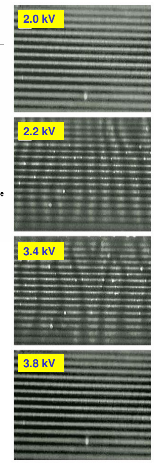
- Most of the DBD patterns have been observed in parallel-plate configurations.
- The Planar DBD plasma was always reported uniform which was operated at high voltage (> 4 kV).

Observation of Moving Stripe Pattern in Planar DBD

Experimental Arrangement:



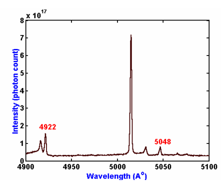
Variation in discharge appearance with voltage:



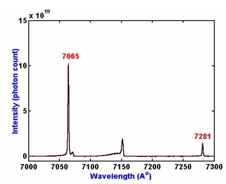
Parameters	Operating range
Pressure	760 Torr
Applied voltage	2-4 kV_{p-p}, sinusoidal
Frequency	10 kHz
Electrode gap	Undefined
Gas Flow Rate	1-5 lpm
Current density	1-5 mA/cm^2
Average power	10- 60 W
Power density	1-10 W/cm^3
e-n collision frequency	3 x 10^{12} per sec
i-n collision frequency	2 x 10^9 per sec

Spectroscopic Plasma Diagnostics

The He-I line intensity ratio method [2] was used to estimate the electron density and temperature. For this purpose the values of plasma parameters corresponding to experimentally observed intensity ratios were obtained from the Fugimoto's numerical code that deals with the Collisional-Radiative (C-R) model approximations.



4922 A°/ 5048 A°
Intensity ratio ~ 2.0
N_e ≈ 1.0 x 10^{11} cm^{-3}



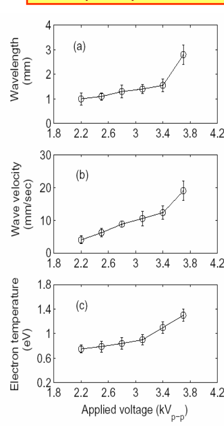
7281 A°/ 7065 A°
Intensity ratio ~ 0.16
T_e ≈ 1 eV

Spatio-Temporal and Spectral Data Analysis

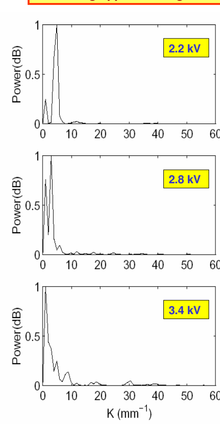
- The CCD captured discharge events were converted to regular images (time gap = 0.04 s).
- The image that shows intensity variation I (x.y), was analyzed with the software ImageJ.
- Spatial and temporal variation of light intensity was obtained at different discharge parameters.

Typical Wave parameters	Estimated Value
Wavelength	~ 2 mm
Wave velocity	~ 1 cm/s
Wave frequency	~ 8 Hz

Effect of applied voltage variation on wave/plasma parameters



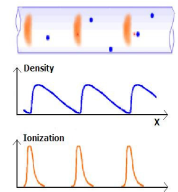
Power spectrums of striations at increasing applied voltage



The analysis shows that experimentally observed moving patterns have similar characteristics as an ionization wave of glow discharge.

Moving Striation or Ionization wave

- Moving striations or Ionization waves are the propagating instability in the positive column of a glow discharge plasma [3, 4, 6].
- It is exhibited in the form of alternate dark and bright regions of light or ionization that shows the spatial variation of electron density.
- The ionization wave shows the characteristics of a backward wave whose frequency may vary from few Hz to few kHz.
- The possible sources of excitation of ionization waves are Electron density and temperature gradients, Thermal instability at high pressure, Step-wise ionization, Metastable destruction, Maxwellization of electrons at high electron density etc.

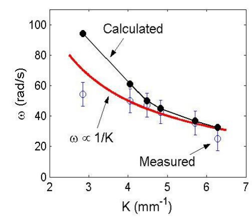


Theoretical Dispersion relation and comparison with Experimental Data

Dispersion relation of the Ionization wave is given by [4]:

$$\omega = ka^2\left(\frac{q}{q-kb}\right)^2\sqrt{\frac{bT_e}{M_i(q-kb)}}\frac{1}{K}$$

$\omega K = constant$



Required condition for a striation to occur in glow discharge [3]:

$K\Lambda_u > 1$

where, K - Wave number

Λ_u - Electron energy relaxation length

$$\Lambda_u = v_d\tau_u \approx 0.8l/\sqrt{\delta}$$

l - electron mean free path

For our experimental parameters:

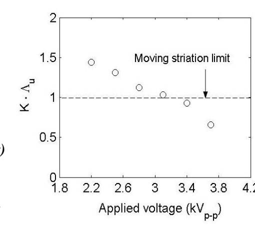
$K = 4.5\ mm^{-1}$

$l = 4.7\ \mu m$

$\delta = 2.7 \times 10^{-4}$ (for Helium at 760 Torr)

Calculated $K\Lambda_u = 1.05$

Hence striation condition is satisfied.



Conclusive Remarks

- The moving striations or ionization waves have been observed in planar dielectric barrier discharge in helium at atmospheric pressure.
- The Plasma parameters i.e. electron density and temperature were measured using optical emission spectroscopy. The measured values along with the current density show the signature of a non-equilibrium glow discharge plasma.
- The consistency of experimental dispersion relation with the theoretical dispersion relation, the backward wave characteristic ($\omega \propto 1/K$) and fulfillment of required criterion ($K\Lambda_u > 1$) prove that the observed striations are Ionization waves.
- Wave frequency and amplitude increases with the voltage, causing damping of ionization waves at higher voltage and a uniform discharge was achieved.
- Helium is a rich source of high energy (~ 20 eV) metastables. The step-wise ionization is prominent process and may leads to excitation of such discharge instability.
- The work provides a mapping of stable and unstable regime of planar DBD plasma. This valuable input may be crucial to use planar DBD for various applications.

References

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