Application of Plasma Phenomena

Lecture 3
2019/3/15
Methods of plasma production

- DC electrical discharges
  - Dark electrical discharges in gases
  - DC electrical glow discharges in gases
  - DC electrical arc discharges in gases
- AC electrical discharges
  - RF electrical discharges in gases
  - Microwave electrical discharges in gases
- Other mechanism
  - Laser produced plasma
  - Pulsed-power generated plasma
Reference

- Industrial plasma engineering, volume 1, by J. Reece Roth, Chapter 8 - 13.
- Plasma physics and engineering, by Alexander Fridman and Lawrence A. Kennedy.
- Plasma medicine, by Alexander Fridman and Gary Frideman.
Electrical discharge physics was studied using the classical low pressure electrical discharge tube.
The V-I curve is nonlinear in a DC electrical discharge tube

- Depends on the voltage, the adjustable ballast resistor, the voltage-current characteristic behaves differently in different regime.
  - Dark discharge
  - Glow discharge
  - Arc discharge
Phenomenology of corona generated by a fine wire

- The point of corona initiation is that point at which the voltage on the inner conductor of radius $a$ is high enough that corona is just detectable.
- The electric field will drop off to the breakdown value at a radius $r_0$ called the active radius.
A corona shield is used to suppress corona

- Cylindrical approximation:

\[ E_s = \frac{V_0}{a \ln(b/a)} = \frac{bV_0}{a b \ln(b/a)} \]

\[ E_s \equiv E_i \quad (E@ \text{surface for corona initiation}) \]

- For \( b=0.5 \text{ m} \), \( V_0=50 \text{ kV} \), \( E_i\sim E_B\sim 3 \text{ MV/m} \)

\[ \frac{E_B b}{V_0} = \frac{3 \times 10^6 \times 0.5}{5 \times 10^4} = 30 = \frac{\alpha}{\ln \alpha} \]

\[ \alpha \approx 150, \text{ i.e., } a = 0.33 \text{ mm} \]
Electrical breakdown occurs when applied voltage is greater than the breakdown voltage

- Primary electrons: electrons from the cathode due to photoemission, background radiation, or other processes.
- Secondary electrons: electrons emitted from the cathode per incident ion or photon created from ionization in gas.
Collision frequency and electron energy gained from electric field are both important to electrical breakdown.

- Collision is not frequent enough even the electrons gain large energy between each collision.
- Electrons do not gain enough energy between each collision even collisions happen frequently.
- The minimum of the Paschen curve corresponds to the Stoletow point, the pressure at which the volumetric ionization rate is a maximum.
Driven piles - prefabricated steel, wood or concrete piles are driven into the ground using impact hammers.
The internal resistance of the power supply is relatively low, then the gas will break down at the voltage $V_B$, and the discharge tube will move from the dark discharge regime into the low pressure normal glow discharge regime.

DC electrical glow discharges in gases

- Glow discharge

![Glow discharge diagram]

- **DARK DISCHARGE**
  - TOWNSEND REGIME
  - SATURATION REGIME
  - BACKGROUND IONIZATION

- **GLOW DISCHARGE**
  - CORONA
  - BREAKDOWN VOLTAGE

- **ARC DISCHARGE**
  - GLOW-TO-ARC TRANSITION
  - THERMAL ARC
The plasma is luminous in the glow discharge regime

- The luminosity arises because the electron energy and number density are high enough to generate visible light by excitation collisions.
Abnormal glow discharge occurs when the cross section of the plasma covers the entire surface of the cathode.

- Normal glow discharge:
- Abnormal glow discharge:
Low pressure normal glow discharge

- **Cathode**: made of an electrically conducting metal, γ, of which has a significant effect on the operation of the discharge tube.

- **Aston dark space**: a thin region with a strong electric field and a negative space charge. The electrons are of too low a density and/or energy to excite the gas, so it appears dark.

- **Cathode glow**: has a relatively high ion number density. The length depends on the type of gas and the gas pressure.

- **Cathode (Crookes, Hittorf) dark space**: has a moderate electric field, a positive space charge, and a relatively high ion density.
Low pressure normal glow discharge

- **Cathode region**: most of the voltage drop (cathode fall) across the discharge tube appears between the cathode and the boundary between the cathode dark space and the negative glow. Electrons are accelerated to energies high enough to produce ionization and avalanching in this region. The axial length will adjust itself such that \( d_c p \approx (dp)_{\text{min}} \) where \( (dp) \) is the Paschen minimum.
Low pressure normal glow discharge

- **Negative glow**: the brightest light intensity in the entire discharge. It has a relatively low electric field and is usually long compared to the cathode glow. Electrons carry almost the entire current in the negative glow region. Electrons which have been accelerated in the cathode region produce ionization and intense excitation in the negative glow, hence the bright light output observed.
Low pressure normal glow discharge

- **Faraday dark space**: the electron energy in it is low as a result of ionization and excitation interactions in the negative glow. The electron number density decreases by recombination and radial diffusion, the net space charge is very low, and the axial electric field is relatively small.
Low pressure normal glow discharge

- **Positive column**: quasi-neutral, the electric field is small and is just large enough to maintain the required degree of ionization at its cathode end. Since the length of cathode region remains constant, the positive column lengthens as the length of the discharge tube is increased.
Low pressure normal glow discharge

- **Anode glow**: the boundary of the anode sheath, slightly more intense than the positive column.
- **Anode dark space**: has a negative space charge due to electrons traveling from the positive column to the anode and a higher electric field than the positive column. The anode pulls electrons out of the positive column and acts like a Langmuir probe in electron saturation in this respect.
Striated discharges

- Moving or standing striations are, respectively, traveling waves or stationary perturbations in the electron number density which occur in partially ionized gases, including the positive columns of DC normal glow discharge tubes.

- [https://youtu.be/Be4RIjMTOWE](https://youtu.be/Be4RIjMTOWE)

[Image of striations in a glow discharge tube]
Obstructed discharges

- The obstructed glow discharge finds many uses in industry, where the high electron number densities generated by such discharge are desired. It will operate with a higher anode voltage. Such high voltage drops are sometimes desirable to accelerate ions into a wafer for deposition or etching purposes.

\[
L < d_c
\]

at the Paschen minimum, i.e., \((pd_c)_{\text{min}}\)

\[
V_c > V_{\text{Paschen}}
\]
Discharge may enter glow-to-arc transition region if the cathode gets hot enough to emit electrons thermionically and the internal impedance of the power supply is sufficiently low, the discharge will make a transition into the arc regime.
Cylindrical glow discharge sources

- This configuration is used in lighting devices, such as fluorescent lights and neon advertising signs.
Parallel plate sources are widely used for plasma processing and plasma chemistry applications

- **Unobstructed operation**

- **Obstructed operation**

  The obstructed configuration is used for plasma processing, where high ion energies bombarding the cathode, over large areas and at vertical incidence, are desired.
Magnetron plasma source are used primarily for plasma-assisted sputtering and deposition

- When several hundred voltages are applied between the parallel plates, a glow discharge will form, with a negative glow plasma trapped in the magnetic mirrors above the magnet pole pieces.
Penning discharge plasma sources produce a dense plasma at pressures far below than most other glow discharges.

- Strong axial magnetic fields: to prevent electrons from intercepting the anode.
- Axial electric fields: electrons are reflected by opposing cathodes.
- Multiple reflection of the electrons along axis.
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Aurora

https://en.wiktionary.org/wiki/aurora
Aurora seen from a satellite

Earth’s magnetic field

http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html
Earth magnetic fields are strongly influenced by solar wind

http://www.pas.rochester.edu/~blackman/ast104/emagnetic.html
Reconnection

https://www.youtube.com/watch?v=7sS3Lpzh0Zw
Corona mass ejection (CME)

http://cse.ssl.berkeley.edu/SegwayEd/lessons/exploring_magnetism/in_Solar_Flares/s4.html#sf
Reconnections occur in many locations

• The Aurora Borealis:
  
  https://www.youtube.com/watch?v=IT3J6a9p_o8

Planeterrella is an aurora simulator
Simple glow discharge is demonstrated
Aurora/ring current are demonstrated

- B w/ magnet: aurora demonstration
- F w/ magnet: ring current
Aurora and ring current are expected to be seen