The Experimental Study on Vacuum Breakdowns by Optical Diagnosis

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Introduction

Experimental Setup
- Parameters
- Procedure

Result
- Light emission during a breakdown
- Light emission with an optical filter
- The effect of a magnetic field
- Spectra during a breakdown

Discussion

Conclusion
Micrometer-size craters can be always found on the surface after vacuum breakdowns.

Not only the cathode but also the anode is affected by breakdowns.

Sometimes, the crater on the anode seems to be even larger than that on the cathode.

The craters are the remains of breakdowns, but cannot provide detail information of the physical processes.

Before we move on, a basic question should be answered: What role do the cathode and anode play in the processes, respectively?
A negative voltage with a peak value of 40 kV

Voltage waveform without breakdown

Measured by PVM-7:
60 kV/100kV, 1000:1, 110 MHz

Current waveform during breakdown

Measured by Pearson Current Monitor 6596: 150 MHz

- **ICCD Camera:** Andor DH334T-18U-04
  - Minimum gate time: 2ns

- **Dual-channel Spectrometer:** SOL NP250-2
  - Spectral resolution: 0.07nm

- **Optical filters:**
  - Center wavelength: 391.42nm (Cu II)
  - Center wavelength: 570.78nm (Cu I)
Parameters of Experiments

- **Gap structure:** tip-tip, tip-plane and triple-tip (The upper is a cathode and the lower is the anode)
- **Magnetic field:** only adopted with the triple-tip structure
- **Material:** Copper, Aluminum (Aluminum is chose because it can provide much higher intensive light than copper, important for spectrum observation)
- **Gap length:** 0.5-5 mm (can be smaller, but difficult to observe the radiance)
- **Pressure:** $10^{-4}$ Pa
The proof of repeatability

- Two independent shots with an exposure time of 5 us:
  - One image is captured at a specific time instant for each shot.
  - After several shots, the whole breakdown process can be presented by joining all the images.
  - The current and voltage waveforms imply that the physical process of vacuum breakdowns is repeatable.
  - The images captured with an exposure time of 5 us, involving a whole process, also indicate the repeatability is good enough.
Procedure of Experiments

- \( t_0 \): start point of current rising
- \( t_1 \): camera gate is opened.
- \( t_2 \): camera gate is closed.
- \( t_w = t_2 - t_1 \): exposure time.
- \( \Delta t = t_1 - t_0 \): when the image is captured.
Results

Light emission during a breakdown process

Exposure time: 5 us; Tip-Plane; Copper

- Gap length: 5 mm
- Gap length: 3 mm
- Gap length: 1 mm

- It is difficult to recognize the radiance from a small gap because of the spatial resolution and development speed.
- We tried to perform an experiment with a gap length of 100 um, but the ICCD cannot work well, so did a streak camera with 2 ps time resolution because the light was weak.
Light emission during a breakdown process

Exposure time: 50 ns; Gap length: 5 mm; Tip-Plane; Copper

Δt  |  -50 ns  |  0 ns  |  50 ns  |  100 ns  |  150 ns  |  200 ns  |  250 ns  |
Δt  |  300 ns  |  350 ns  |  400 ns  |  450 ns  |  500 ns  |  550 ns  |  600 ns  |
Δt  |  650 ns  |  700 ns  |  750 ns  |  800 ns  |  850 ns  |  900 ns  |  950 ns  |
Results

Light emission during a breakdown process

Exposure time: 50 ns; Gap length: 3 mm; Tip-Plane; Copper

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Exposure time: 50 ns; Gap length: 5 mm; Tip-Plane; Copper

- Some information could be hidden by the strongest lighting area, so the contrast ratio is adjusted to make the process clear.
- The process can be divided into 3 stages:
  1) Light was emitted from the cathode tip.
  2) The anode started glowing.
  3) The glowing region near the anode expanded to the cathode.
- The light emitted from the cathode was restricted to a small region around the tip, but, on the contrary, the glowing region gradually covered the anode surface and expanded to the cathode.
The time point of anode glowing was coincided with the time point when the current ceased rising.

The stable current amplitudes were the same because of the same external impedance.
Results

Light emission with an optical filter: Cu I

- Center wavelength: 570.78nm (Cu I)
- Copper atoms were observed near the cathode at the initial stage, similar to the previous results as well as the appearing time of copper atoms near the anode.
- The brightness around the cathode is slight higher than that around the anode.

Exposure time: 50 ns;
Gap length: 3 mm;
Tip-Plane;
Copper
Center wavelength: 391.42nm (Cu II)

It seems that the distribution of single-charged copper ions is similar to that of copper atoms, but more scattered.

The brightness around the cathode is not higher than that around the anode, even lower than that.

Exposure time: 50 ns;
Gap length: 3 mm;
Tip-Plane;
Copper
A triple-tip structure combined with a magnetic field was adopted to verify which kind of particles, electrons or ions, are responsible for the anodic glowing.

We assumed that all the initial particles come from the cathode tip.

Apparently, electrons caused the anode glowing based on the estimation of Lorentz force.

A stronger magnetic field could make this phenomena more clearly.

Exposure time: 5us; Gap length: 3 mm; Magnetic field: 280 mT; Triple-tip; Copper
A dual-channel spectrometer was adopted to detect the spectral lines in different wavebands instantaneously.

The spectral lines of Al I indicate that the distribution of Al atoms is uniform.

The multi-charged ions, Al II and Al III, are concentrated near the cathode.

However, we also observed some contradictions when the material was not aluminum, so further experiments are required.
The electrons emitted from the cathode are responsible for heating up the anode, leading to evaporation on it.

Anode glowing is attributed to the evaporation of the anode material otherwise a clear glowing bridge should be observed as well as atom distribution.

For a gap within a millimeter level, the atoms from the anode is important for forming a stable discharging tunnel.

For a very tiny gap, forming a stable discharging tunnel does not require the evaporation from the anode because the vapor from the cathode can reach the anode even the radiance near the cathode is restricted to a small region.

Therefore, the craters on the anode could be caused by the plasma from the cathode or evaporation on it.
A breakdown is triggered on the cathode, and the anode also plays a crucial role in forming a stable discharging channel.

The light is restricted to a small region near the cathode tip in a breakdown process.

The light near the anode, after the light emission of the cathode, gradually intensifies and expands to the cathode.

The electrons from the cathode heat up the anode, leading to an anode glowing.

**Future plan:**

Adopting an interferometer to quantitatively measure the parameters of the plasma during breakdown.
Thank you for your attention!