Roles and Physical Processes of Anodes in the Initial Stage of Vacuum Breakdowns

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OUTLINE

- Background and Motivation
- Experimental Setup
- Results
- Discussion
- Conclusions
**Stage I:** Cathode glows right after a BD occurs.

**Stage II:** Anode starts to glow and expand to the cathode.

**Stage III:** Light emission near the anode decay gradually, while the cathode glow remains until the end of the voltage pulse.

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Zhenxing Wang @ Xi'an Jiaotong University
The voltage collapses **well before** the gap is bridged by the expansion of anode light.

The expansion of anodic glow seems **NOT** contribute much to the formation of the conductive channel.

### Stage II

<table>
<thead>
<tr>
<th>Gap Length (mm)</th>
<th>Start</th>
<th>End</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 mm</td>
<td>250</td>
<td>2050</td>
<td>1800</td>
</tr>
<tr>
<td>3 mm</td>
<td>150</td>
<td>850</td>
<td>700</td>
</tr>
<tr>
<td>1 mm</td>
<td>40</td>
<td>300</td>
<td>260</td>
</tr>
<tr>
<td>0.5 mm</td>
<td>10</td>
<td>150</td>
<td>140</td>
</tr>
</tbody>
</table>

- **Anode glow starts**
- **Gap bridged by the glow**

Time instants when gap voltages drop to zero.

Time instants of anode glow
There are two questions left by the previous paper:

- Do anode materials have significant affect on the glowing process?

- Which physical processes contribute more to the anode glow?
General description

- Electrical discharges occurred in a demountable stainless steel chamber;
- The chamber was pumped to a pressure of $2.5 \times 10^4$ Pa;
- A pair of tip-to-plane electrodes were installed with a variable gap length;
- The impulse voltage source provided a negative high voltage ranging from 0 to 50kV with a pulse width between 1 µs to 5 µs;
- The anode material varied among Al, Cr, Cu, Mo, Ni and W, while the cathode material was always Cu.

Schematic diagram of the experimental setup

Structure and working principle for a streak camera

Sample image of the electrodes and gap

Electrode configuration
I: Typical electrical waveforms

- The gap length was 5mm, and the steady current was 60A 80A;
- The starting point $t_{BD}$ of a breakdown is defined as time zero;
- The end point $t_{FB}$ indicates the transition from vacuum flare to vacuum arc and a fully conductive electrical path was formed.
The horizontal axis represents time lapsing rather than positions in space; $t_{CG}$, starting point of cathodic glow; $t_{AG}$, starting point of anodic glow; $t_E$, time point of voltage source turn-off; The intensity of anodic glow did not grow continuously but decayed a short time later, while the cathode kept glowing until $t_E$. 
RESULTS

III: Effect of anode materials

- The anode material seems not to have much effect on the delay for the anodic glow;
- The delay increases almost linearly with the gap length.
The voltage collapse indicates the formation of the conductive channel in the gap;

It is easier for an anodic glow to be appeared before a voltage collapse at higher currents and shorter gaps;

If the gap length becomes much larger, the anodic glow occurs much later than the moment of the voltage collapse.

Anodic glow is NOT the prerequisite for the voltage collapse or the formation of conductive channel.
The voltage of different cases fluctuate around 21kV, and there is no obvious pattern that can be observed. It further proves that the anode does not play a critical role in the initial stage of a vacuum breakdown.
I: Energy deposited by electrons

Current waveforms | Voltage waveforms | Accumulated deposited energy on the anode surface

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_i$(ns)</td>
<td>357.9</td>
<td>292.6</td>
<td>256.5</td>
<td>241.7</td>
<td>296.3</td>
</tr>
</tbody>
</table>

- The deposited energy on the anode surface by electrons at the initial stage of a vacuum breakdown is calculated:

$$E(t) = \int_{t_{BD}}^{t} V(t) \times I(t) \, dt$$

- We found that there did not exist a specific energy level that could indicate anodic glow.
II: Evaporation on anode surface

We assumed that the electron beam has a Gaussian distribution with $\sigma = 1$ mm. Then the heat source for the anode is calculated as $P(t) = V(t)I(t)/(2\pi\sigma^2)$; the number density of the evaporated atoms is calculated according to the saturated vapor pressure; the great difference in evaporated atom densities for different anode materials would also result in difference in the delay for the anodic glow, if all the atoms in the glow region come from the evaporation of the anode surface.
III: Sputtering process on anode

- Adopting the Binary Collision Approximation method to calculate the sputtered atom velocity

Ion flux density at the anode surface:

\[ Q = \frac{I_{\text{ion}}}{e} \frac{1}{2\pi\sigma^2} = 7.96 \times 10^{24} \text{ m}^{-2} \cdot \text{s}^{-1} \]

Sputtered atom density:

\[ n_{\text{sput}} = \frac{QY}{v_{\text{sput}}} \]

<table>
<thead>
<tr>
<th>Anode materials</th>
<th>Al</th>
<th>W</th>
<th>Cr</th>
<th>Cu</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sputtering yield Y</strong></td>
<td>0.164</td>
<td>0.134</td>
<td>0.326</td>
<td>0.591</td>
<td>0.133</td>
<td>0.276</td>
</tr>
<tr>
<td><strong>Average sputtered atom</strong></td>
<td>energy (eV)</td>
<td>3.49</td>
<td>11</td>
<td>5.12</td>
<td>6</td>
<td>8.01</td>
</tr>
<tr>
<td><strong>Average sputtered atom</strong></td>
<td>velocity (m/s)</td>
<td>4994</td>
<td>3394</td>
<td>4355</td>
<td>4250</td>
<td>4009</td>
</tr>
<tr>
<td><strong>Sputtered atom density(m^{-3})</strong></td>
<td>2.61e20</td>
<td>3.14e20</td>
<td>5.96e20</td>
<td>1.11e21</td>
<td>2.64e20</td>
<td>4.95e20</td>
</tr>
</tbody>
</table>
DISCUSSION

IV: Comparison of sputtered and evaporated atoms

<table>
<thead>
<tr>
<th>Radius</th>
<th>Anode materials</th>
<th>Al</th>
<th>W</th>
<th>Cr</th>
<th>Cu</th>
<th>Mo</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sputtered atom density (m⁻³)</td>
<td>2.61e20</td>
<td>3.14e20</td>
<td>5.96e20</td>
<td>1.11e21</td>
<td>2.64e20</td>
<td>4.95e20</td>
</tr>
<tr>
<td></td>
<td>Evaporated atom density (m⁻³)</td>
<td>1.82e22</td>
<td>6.03e11</td>
<td>4.83e22</td>
<td>2.58e17</td>
<td>3.17e16</td>
<td>1.91e21</td>
</tr>
<tr>
<td>σ=1 mm</td>
<td>Sputtered atom density (m⁻³)</td>
<td>6.53e19</td>
<td>7.85e19</td>
<td>1.49e20</td>
<td>2.78e20</td>
<td>6.60e19</td>
<td>1.24e20</td>
</tr>
<tr>
<td></td>
<td>Evaporated atom density (m⁻³)</td>
<td>8.05e4</td>
<td>3.42e-30</td>
<td>2.14e6</td>
<td>9.14e-3</td>
<td>2.28e-14</td>
<td>3.87e3</td>
</tr>
<tr>
<td>σ=2 mm</td>
<td>Sputtered atom density (m⁻³)</td>
<td>6.53e19</td>
<td>7.85e19</td>
<td>1.49e20</td>
<td>2.78e20</td>
<td>6.60e19</td>
<td>1.24e20</td>
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</tr>
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</table>

- The sputtering process of anode surface under the impact of cathode ions is an important source for the atoms in the anodic region;
- The contribution of this process may well exceed that of the evaporation process for refractory anode materials such as W and Mo;
- Here, we do not discuss the atoms from the cathode. From the spectroscopic experiments, they DO indicate that the cathode materials contribute a lot to the anodic glow. But we need further experimental results to verify this point.
CONCLUSIONS

- A fully conductive channel after a vacuum breakdown triggered can be established without contributions from the anode, and the anode material does not affect this process significantly;

- Different anode materials did not affect the delay times between the cathodic and anodic glow obviously as well as the breakdown voltages;

- The evaporation of the anode surface under the heating of electrons can not be the major source generating the vapor atoms in the anodic region;

- The ion sputtering process at the anode surface are important source for the vapor atoms in the anodic glow region;
CONCLUSIONS

- The interaction between the incident ions and the anode surface can produce low speed neutral atom and electrons, and these particles can collide with each other at a higher probability than those in the middle of the gap, resulting in the anodic glow.

- We will verify the contributions of the cathode materials by further experiments.
Thank you for your attention!