Physics of high-current diode

Lie Liu
National University of Defense Technology
Changsha, Hunan 410073, China
Content

1. Electron emission mechanisms and fabrication of cathode
2. Plasma formation and diagnostics in high-current diode
3. Experimental investigation of anode physics
4. Applications in different high power microwave (HPM) sources
5. On-going research
Schematic of high-current diode

PIC simulation

High-power microwave
1. Cathode emission physics

Explosive electron emission only

E \sim \sigma \sim r^{-2}

- Fast plasma expansion velocity
- Time delay in plasma appearance
- Non-uniformity in plasma distribution

Surface flashover

- Low electric field threshold of electron emission (few kV/cm)
- Quasi-constant diode impedance behavior
- CsI coating superior diode operation
1. Explosive electron emission
2. Surface flashover
3. Additional photo-electron emission with CsI coating

Hybrid emission mechanisms

Carbon Fiber Cathode

1. Explosive electron emission
2. Surface flashover
3. Additional photo-electron emission for CsI (good UV emitter) coating

Thus, we can conclude that an optimized cathode should have several electron emission mechanisms, and thus the uniformity of the whole electron emission surface of the cathode may be increased.
Property of carbon fiber

1. Light weight, high strength, high modulus
   carbon fiber density: 1.6~2.15g/cm³
   tensile strength: >2.2GPa
   modulus: >230GPa

2. Low coefficient of thermal expansion
   Room temperature: (-0.5~-1.6)×10⁻⁶/K,
   at 200~400°C: zero
   at <1000 °C: 1.5×10⁻⁶/K

3. Electric property between metal and non-metal

4. Boiling Point/Range: >3600°C
   Melting Point/Range: Not available

5. Excellent chemical resistance
How to construct carbon fiber cathodes?

Robust (long life), easily shaped, and free-epoxy (Invention Patent No. 200310102051.7)

The advantages carbon-fiber cathode for electron emission:

- larger field amplification factor.
- lower turn-on field and threshold field for emission.
- higher intensity of electrical current.
- better uniformity in emission.
- lower plasma expansion velocity.
- stronger to stand against the bombardment (long life)
Scanning electron microscope (SEM) image of carbon fiber cathode (side)
Energy distribution spectrum (EDS) of the materials on the carbon fibers with and without CsI coating

Without CsI coating

With CsI coating
Properties of ideal pulsed electron source

- Low electric field threshold for electron emission (<50 kV/cm)
- Nanosecond timescale turn-on
- Long life-time (>10^7 pulses)
- High current densities (kA/cm^2)
- Quasi-constant perveance of the diode, a slow plasma expansion rate
- Uniformity and arbitrary cross-section
- Vacuum (10^{-4} – 10^{-5} Torr) compatibility, low outgassing rate
- Low power consumption
2. Diagnostics in diode

High-speed camera

Testing system of optical assistant diagnostics

Testing system of diagnostics
A Mach-Zehnder interferometer was designed and used to measure the plasma density in the diode.
Expansion of Plasma in Diode

Gap distance 1.9cm

- **Cathode turn-on at t=0 ns**
- **Quasi-equilibrium process during t=0-400 ns**
- **Inertial characteristic or anode plasma or both after t=400 ns**
High current densities (kA/cm²)

Emitting spots

Time-and-space resolved observations
X-ray imaging in time and space
(Scintillator film (EJ-260) attach to anode)

Spectroscopic diagnostics

Stark broadening $\rightarrow$ Plasma density: $(4.5 \pm 1.3) \times 10^{14}\text{cm}^{-3}$

$H_\alpha / H_\beta$ population ratio $\leftrightarrow$ Collisional radiative modeling

Plasma electron temperature $7 \pm 2$ eV

The images depict various wavelength spectra and molecular structures. The graphs show the intensity (arb. u.) vs. wavelength (Å) for different elements:

1. **Cs II 4603.79 Å**
2. **C I 2478.56 Å**
3. **CII, 4267.3 Å**
4. **C III, 4255.4 Å**

The molecular structures include:
- Cs
- I
- C

The rightmost image appears to show a laboratory setup with various equipment, possibly related to the research on these wavelengths and molecular structures.
“Cs plasma” remains at the vicinity of the cathode surface, Cs II (4603.8 Å) was obtained only at the distance of 2.5mm from the cathode surface.
Vacuum compatibility

Velvet cathode

Carbon fiber cathode
Velvet cathode, 20 Hz, 10 pulses

Carbon fiber cathode, 50 Hz, 10 pulses
The anode grid is of 21 cm in diameter and 70% transparency. The square grid cell’s inner length is about 2.5 mm with cylindrical single wire of 0.3 mm in diameter.

3. Surface morphology of the stainless steel anode-grid irradiated by high-current electron beams
Surface morphology of a single wire observed by a SEM in increasing magnification

**Question:**
Is it Rayleigh-Taylor-like interface instability?
4. A series of tufted carbon fiber cathodes designed for different high power microwave sources
Carbon fiber-based cathodes for magnetically insulated transmission line oscillator (MILO) operation

Carbon fiber velvet cathode for MILO operation

Large-Area uniformly emitting
5. On-going research: cathode with carbon nanotube (CNT) coating

Large-area uniformly CNT on cathode surface

Scanning electron microscope (SEM) image of CNT on cathode surface
U_d = 318kV  \quad I_d = 84.5kA
Laser cladding (or by high-current electron beams)

Laser cladding to make carbon nanotube cathode
CNT cathode surface through laser cladding can generate field enhanced EEE and surface-flashover EEE.
What methods can be used to improve the cladding uniformity of carbon nanotube on a cathode?

- Digging holes on the surface of cathode uniformly
- Fill carbon nanotube powder into these holes
- Apply laser cladding to combine them together
Recent research breakthroughs include novel methods to precisely fabricate new high current density cathodes and improved understanding of cathode emission physics.
Results from US Air Force Research Lab

Current Variation Over 1 Hour at 1 Hertz
1 Trace every 10 minutes
250 kV

Fig. 4. Current obtained for operation at 250 kV over a period of 1 h. We acquired current data every 10 min. Current remains very stable throughout operation.

TABLE I
VOLTAGE, CURRENT, CURRENT DENSITY, AND SHOT NUMBERS FOR CNT CATHODE. NOTE THAT AVERAGE CURRENT DENSITY OVER MACROSCOPIC REACHES 50 A/cm²

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Current (kA)</th>
<th>Current Density (A/cm²)</th>
<th>Number of Shots</th>
</tr>
</thead>
<tbody>
<tr>
<td>137.5</td>
<td>0.8</td>
<td>12.5</td>
<td>5,000</td>
</tr>
<tr>
<td>165</td>
<td>1.3</td>
<td>20.3125</td>
<td>5,000</td>
</tr>
<tr>
<td>192.5</td>
<td>1.5</td>
<td>23.4375</td>
<td>5,000</td>
</tr>
<tr>
<td>220</td>
<td>1.7</td>
<td>26.5625</td>
<td>5,000</td>
</tr>
<tr>
<td>247.5</td>
<td>2.2</td>
<td>34.375</td>
<td>5,000</td>
</tr>
<tr>
<td>275</td>
<td>2.5</td>
<td>39.0625</td>
<td>5,000</td>
</tr>
<tr>
<td>302.5</td>
<td>3</td>
<td>46.875</td>
<td>5,000</td>
</tr>
<tr>
<td>330</td>
<td>3.3</td>
<td>51.5625</td>
<td>3,321</td>
</tr>
</tbody>
</table>
Results from China Academy of Engineering Physics & University of Science Technology Beijing

What one can get from the Project

1. Paper __ physics and more discussion

(Comments from APL referees about my papers)

Paper Interesting: Yes Original Paper: Yes Sufficient Physics: Yes
Well Organized: Yes Clear and Error Free: Yes Conclusions Supported: Yes
Appropriate Title: Yes Good Abstract: Yes Satisfactory English: No
Adequate References: Yes Clear Figures: Yes

2. Applications __ fabrications and materials

The cathode material:
Low electric field (<50 kV/cm) for electron emission, Nanosecond timescale turn-on,
Long life-time (>10^7 pulses), High current densities (kA/cm^2)
a slow plasma expansion rate (coating technique), Uniformity and arbitrary cross-section
Vacuum (10^{-4} – 10^{-5} Torr) compatibility (low outgassing rate), Low power consumption
The fabrication process and cathode structure: How to construct cathodes,
Robust (long life), easily shaped, free-epoxy and surface treatment technique of cathodes

Overall rating Something new and detailed
Acknowledgement

National Natural Science Foundation of China (No. 10975186).

Some optical assistant diagnostics of plasma in diode were accomplished during the author’s visit in Physics Department of Technion-Israel, collaborating with Prof. Krasik and his group!