CONSORTIUM

Performance of the low power heaterless plasma discharge (HPD) cathode for electric propulsion applications in small satellites

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Motivation : Development of low power cathodes for small/micro satellites

Requisites for cathodes intended for electric propulsion applications in nano and micro satellites (size, electric power, gas consumption …) *are very demanding.* Hence, the implementation of conventional electron sources based on thermionic electron emission in nano and micro satellites is an issue.

- Thermal stresses are important in *conventional Hollow Cathodes* (HC) where *thermionic electrons* from a heated (T>2000 K) insert material produce the *partial ionization of a neutral gas flow*.
- The new *Heaterless Hollow Cathodes* (HHC) are aimed at avoiding the HCs high temperatures of operation. A high voltage electric discharge is triggered two electrodes in a gas flow. In this case, the *electron thermionic emission is produced by the ohmic heating of electrodes* by the plasma discharge current (see section 5 of reference cited below).

The objectives of present add-on outcome from the NEMESIS project are:

- Explore the replacement of the *secondary electron emission (SEE) by ion impact* as a mechanism to deliver a low current of free electrons
- The development of a *laboratory prototype of a low power cathode* based on SEE.
- The search for additional applications of the C12A7:e- electride material compared to LaB_6

D.R. Lev, I.G. Mikellides, D. Pedrini, D.M. Goebel, B.A. Jorns and M.D. McDonald. *Recent progress in research and development of hollow cathodes for electric propulsion*. Rev. Mod. Plasma Phys. **3**:6 (2019).

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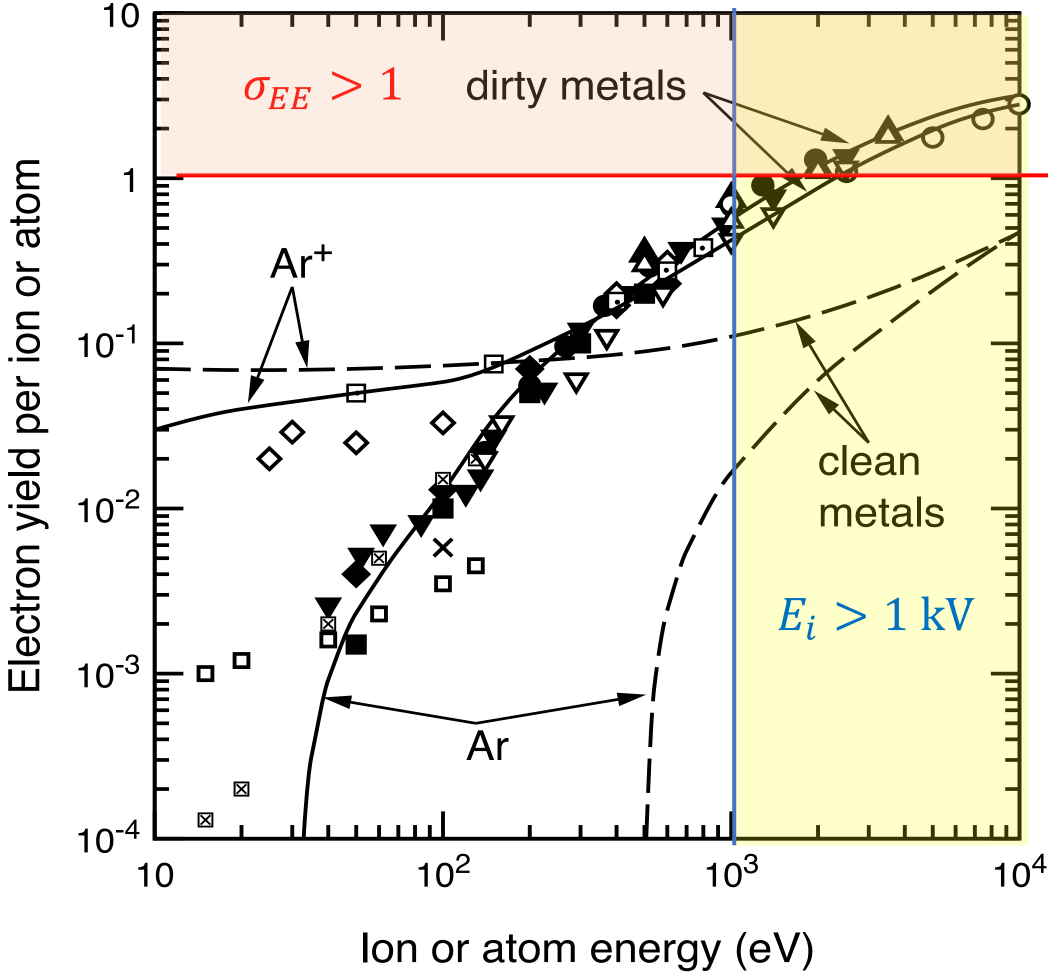
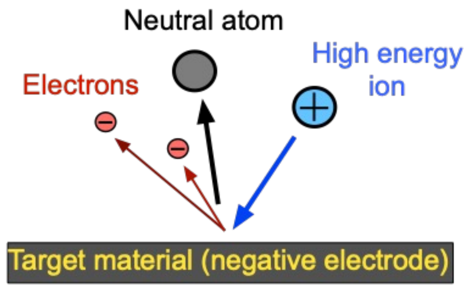
HPD cathode physical principle : Secondary electron emission by ion impact





- The *production of electrons is driven by the kinetic energy of the ions* impacting a target electrode. Symbols in figure indicate different target materials.
- The yield of electrons per ion σ_{SEE} is a statistical concept that characterizes the average number of emitted electrons produced by the impact of one ion.
- *We need a group of ions with energies in the KeV range to obtain* $\sigma_{SEE} > 1$ or production of more electrons than ions are lost.
- *Temperature of target electrode is less relevant* than in thermionic thermionic emission and/or hollow cathode discharges.
- However, *SEE electron currents are much lower* than in thermionic emission process.

- A.V. Phelps and Z. Lj. Petrovic. *Cold-cathode discharges and breakdown in Argon: surface and gas phase production of secondary electrons.* Plasma Sources Sci. Technol. **8** (3) R21-R44 (1999). https://doi.org/10.1088/0963-0252/8/3/201

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The low power heaterless plasma discharge (HPD) cathode/plasma source

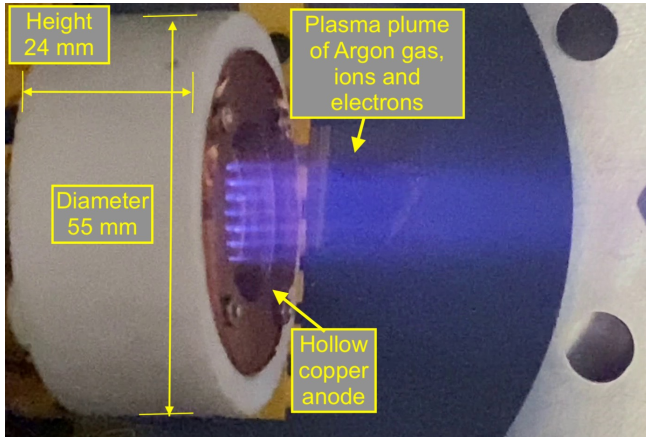

Fig. 1: Upper of view HPD cathode in operation inside the vacuum tank

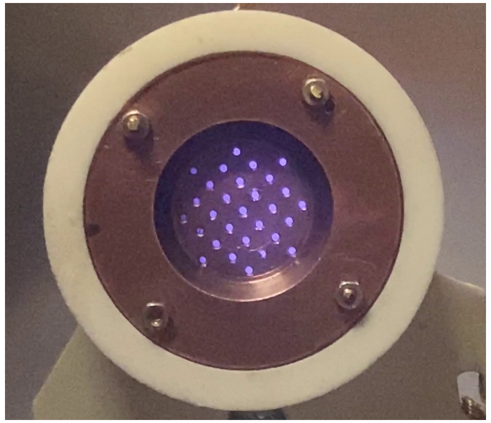

Fig. 2: Front view of HPD cathode in operation inside the vacuum tank

- A plasma is produced by *DC high voltage and low current plasma discharge* between two parallel electrodes in a gas flow.
- Instead of thermionic emission, *electrons are produced by ion impact* at the surface of the electrode connected to a positive voltage. A fraction of electrons leak from the electric discharge to the vacuum tank through the anode holes.
- *Operation temperatures are much* lower than with thermionic electron emission since no electrode heating is needed for the electron emission.
- Consequently, HPD plasma prototype can be made with *simple materials* we have available at hand (teflon body, copper electrodes, …).
  - 55 mm in diameter and 24 mm of length.
  - Argon mass flow rate $\dot{m} \leq 6\ \mathrm{sccm}$
  - Background Argon pressure: $p_a = 1 - 3 \cdot 10^{-3}\ \mathrm{mbar}$
  - No pressure surge is needed to trigger the plasma discharge.
  - DC electric discharge: $V_{ds} = 600 - 1500\ \mathrm{volts} : I_{ds} \sim 3 - 10\ \mathrm{mA}$
  - Electric power consumption: $P_W = 1.8 - 30\ \mathrm{W}$

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HPD cathode performance : Current-Voltage (IV) characteristic curves

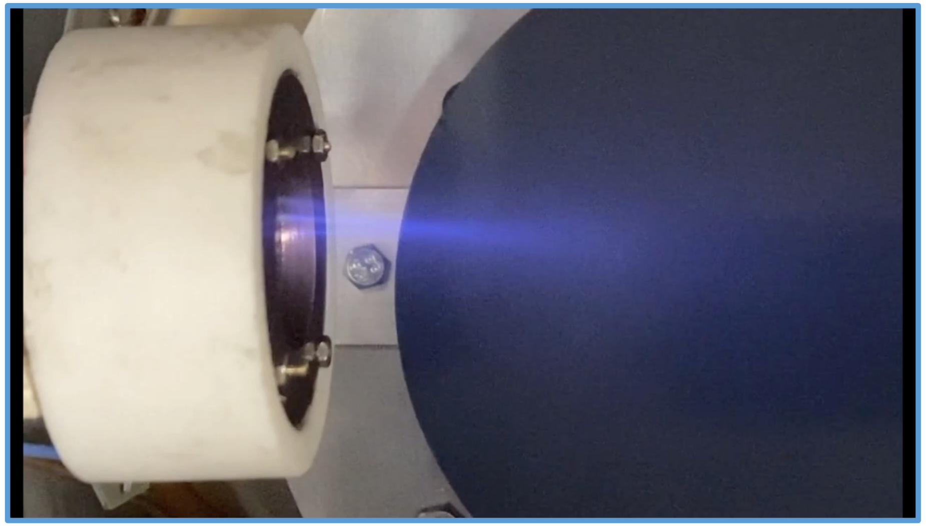

Fig. 4: Plasma plume of the HPD cathode in the experiment of Fig. 6. Real time scale.

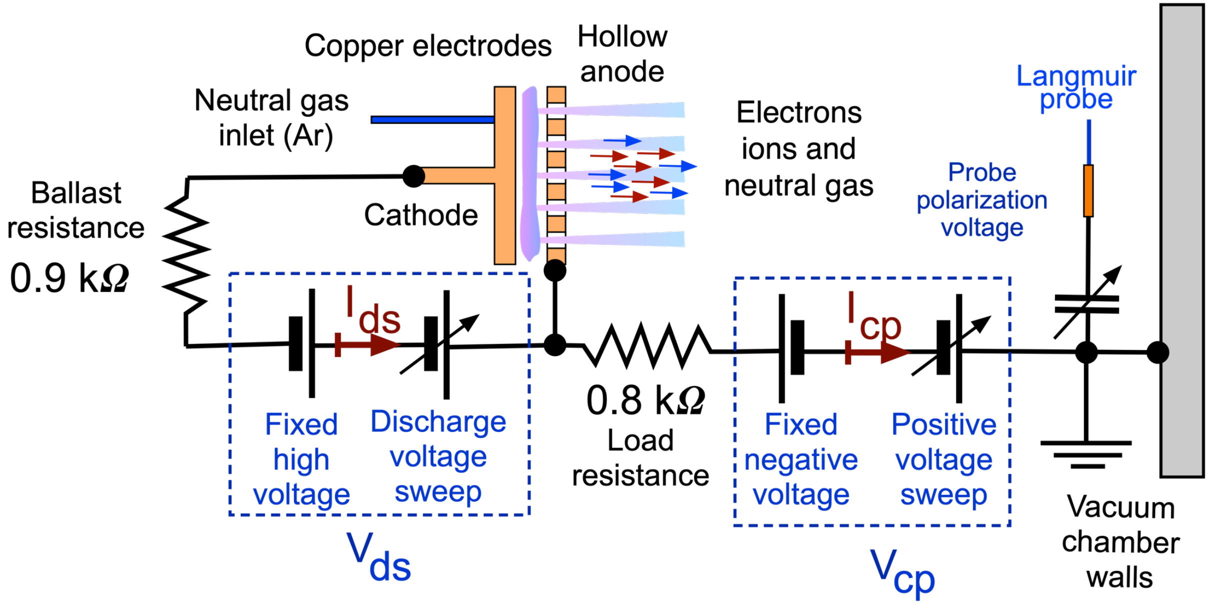

Fig. 5: Electrical scheme of the HPD cathode testing and flow chart for voltage current (IV) $I_{cp}(V_{cp})$ curves.

Equipment	Characteristics	Function
- FUG	- Power supply 1.5 kV / 1.5 A	- Fixed HPD discharge voltage $V_{ds} \sim 0.6 / 1.5$ kV
- Agilent N5771A	- Power supply 300 V / 5 A	- Sweep HPD discharge voltage $V_{ds} \sim 0 / 300$ V
- LAB-SP	- Power supply 200 V / 5 A	- Fixed negative HPD polarization voltage $V_{cp} \sim -90/ 0$ V
- Agilent N5770A	- Power supply 150 V / 10 A	- Sweep positive HPD polarization voltage $V_{ds} \sim 0 / 300$ V
- Keithley 2700	- Multimeter	- Measurement of $I_{cp}(V_{cp})$ cathode polarization current.
- Langmuir probe	- Cylindrical; $\phi = 0.89\, mm, L = 22.59\, mm.$ Sweep rate; 200 IV curves per second	

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HPD cathode testing : Understanding the $I_{cp}(V_{cp})$ characteristic curves

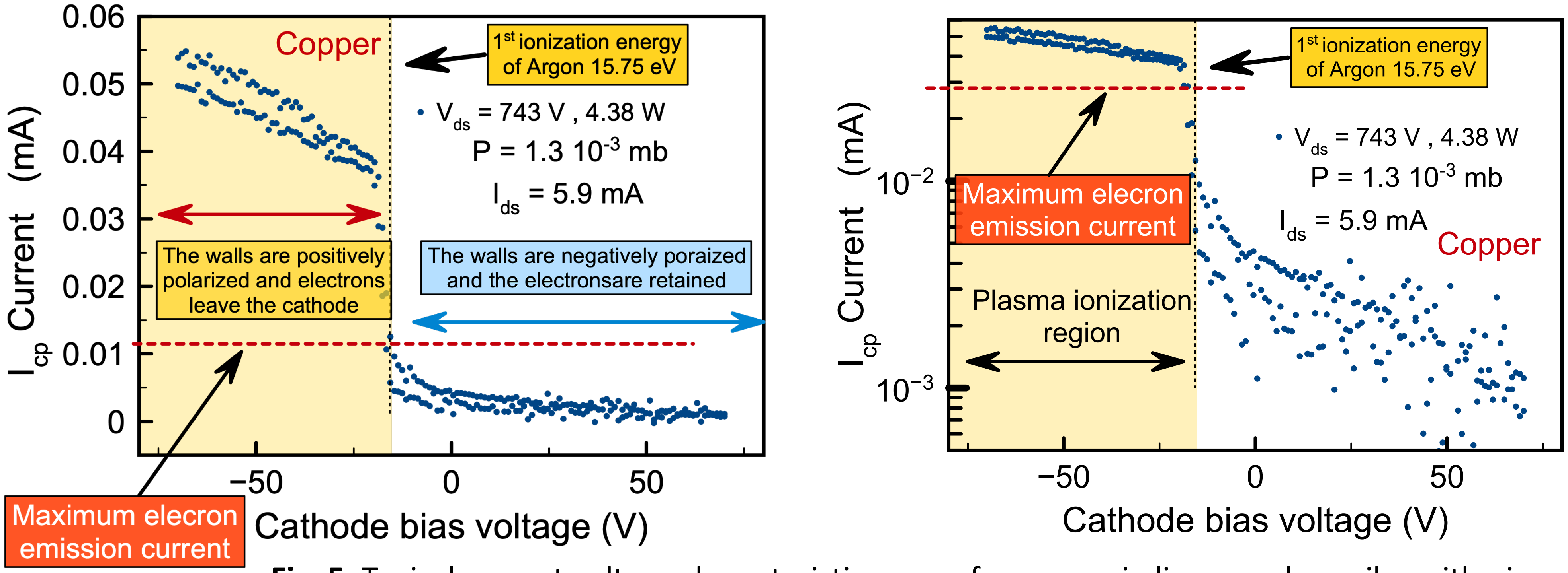

Fig. 5: Typical current voltage characteristic curves for copper in linear and semilogarithmic axes.

- Copper is a reference material with high work function used as a reference in present study.
- The plateau for $V_{cp} \ll -15.76\ \mathrm{V}$ is associated to the *maximum electron emission current* $I_{mx} \sim 0.04\ \mathrm{mA}$ that is a small fraction (below 1%) of the discharge current $I_{cp} \sim 5.9\ \mathrm{mA}$.

Electron emission performance for copper:

$$\eta = \frac{I_{mx}}{P_W} \simeq \frac{0.02}{4.38} = 0.005\ \mathrm{mA\ /\ W}$$

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HPD cathode performance : The LaB6 current-voltage characteristic curves

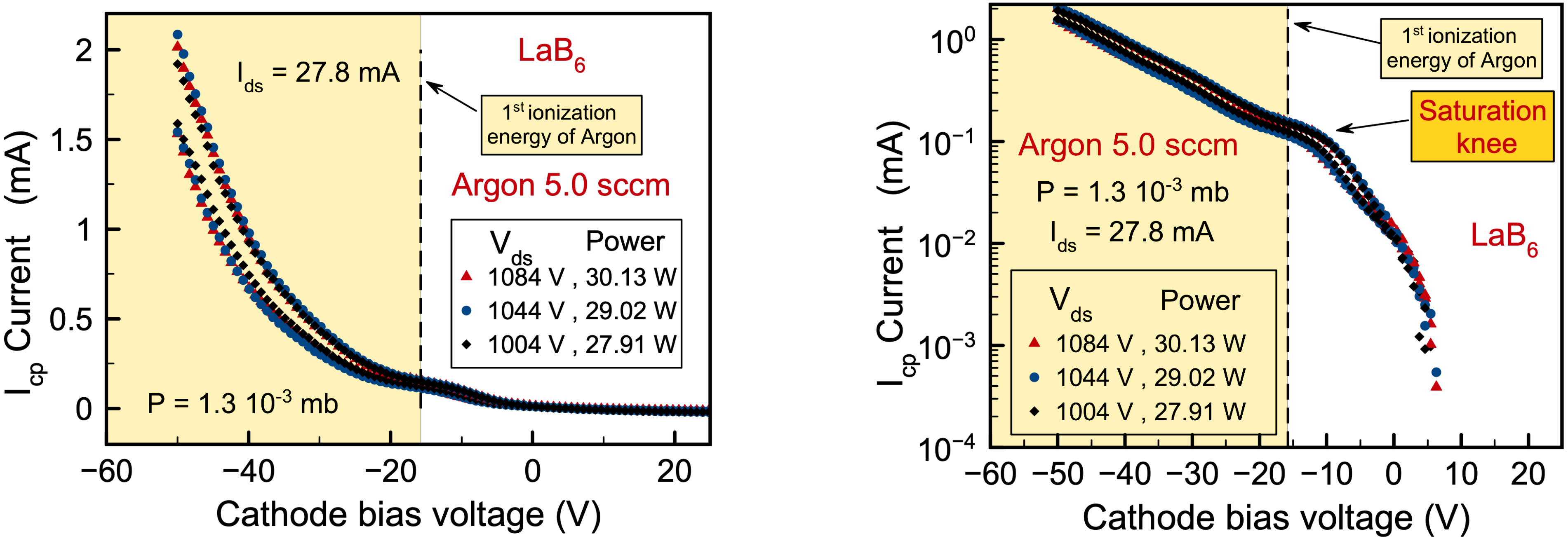

Fig. 6: Typical current voltage characteristic curves for lanthanum hexaboride in linear and semilogarithmic axes.

- Lanthanum hexaboride (LaB$_{6)}$ has a low work function and then its maximum electron emission currents $I_{mx} \simeq 0.2$ mA (saturation knee) are a 5 times higher than for copper.
- Electric power scales up as LaB$_6$ is involved currents increase.

Electron emission performance for LaB$_6$:

$$\eta = \frac{I_{mx}}{P_W} \simeq \frac{0.2}{28} = 0.007 \text{ mA / W}$$

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HPD cathode performance : C12A7:e- current-voltage characteristic curves

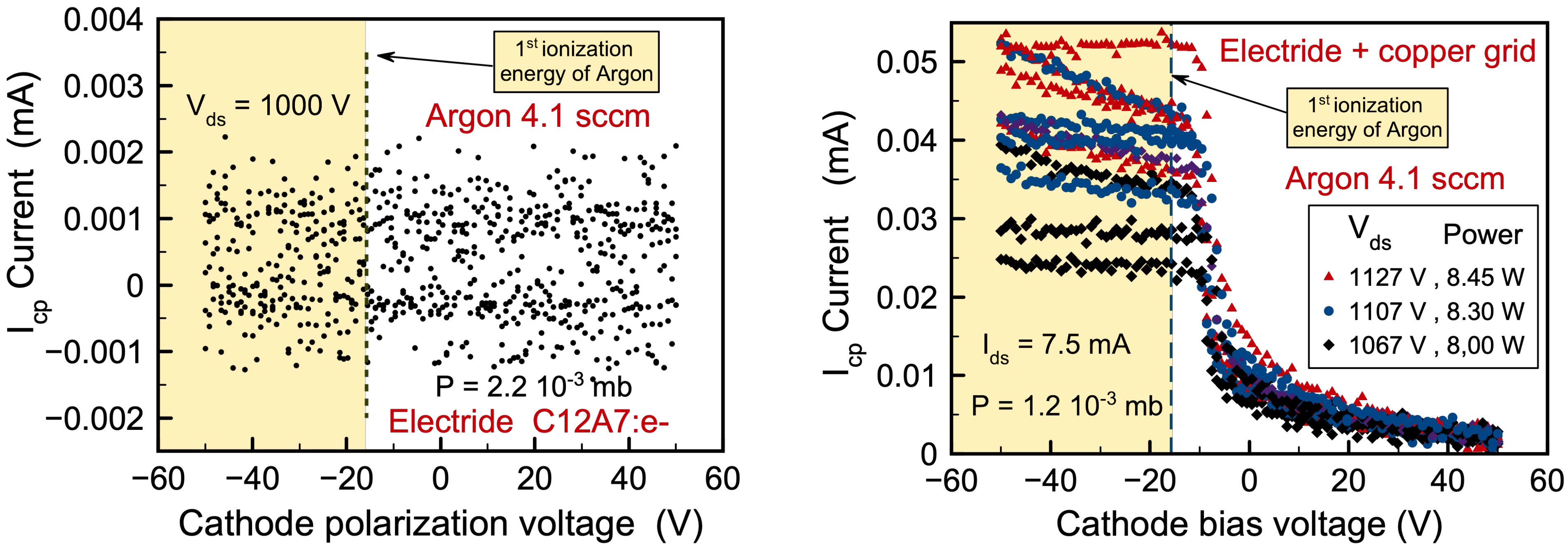
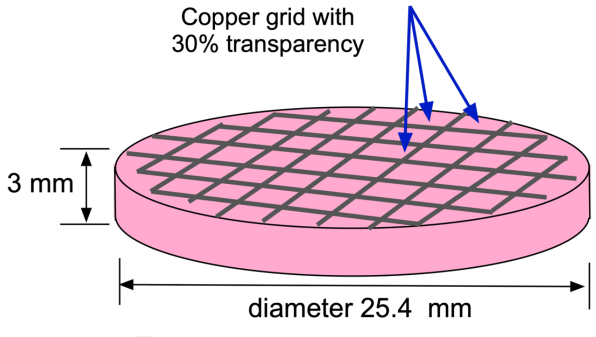


Fig. 7: typical current voltage characteristic curves for C12A7:e- in linear and semilogarithmic axes.

- Initial results for the C12A7:e- electride material were disappointing.
- A notable improvement was observed if we put a conductive grid on the surface of the material bombarded by the ions.
- The low performance is basically related with the low electric conductivity of the electride material.



Electride material slab heated from below

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Conclusions and outlook

Positive:

- *Secondary electron by ion impact can be an alternative to* thermionic electron emission when hen required electron currents are low. In our tests, *thermionic emission is negligible* due to *the low temperature of operation.*
- Contrary to conventional hollow cathode discharges, HPD cathode operates with *low currents* and *high voltages* and *low electric power consumption*.
- Low temperatures of operation allow the use of *simple materials* (copper, teflon, …), there is room for miniaturization using more sophisticated insulators, etc.
- We the HPD cathode delivers higher electron emission currents when *using of a low work function material (such as the C12A7:-e electride or LaB$_6$)* for the target (negative) electrode.

Fig. 8: The inner (negative) electrode of copper after few hours of continuous operation

Negative:

- As shows the photograph the *ion bombardment erodes* the surface of the inner (negative) electrode.
- Gas flow and distribution of neutral atoms in these small volumes is not a trivial issue.
- Temperatures of operation must remain low since ohmic heating of electrode can produce the evaporation of material and brings a transition to arc discharge can damage the HPD cathode.

Thank you for you time and interest

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