Tel Aviv University

Electrical Discharge and Plasma Laboratory

Depart of Electrical Engineering - Physical Electronics

Experimental Study of Vacuum Arcs with Refractory Anodes

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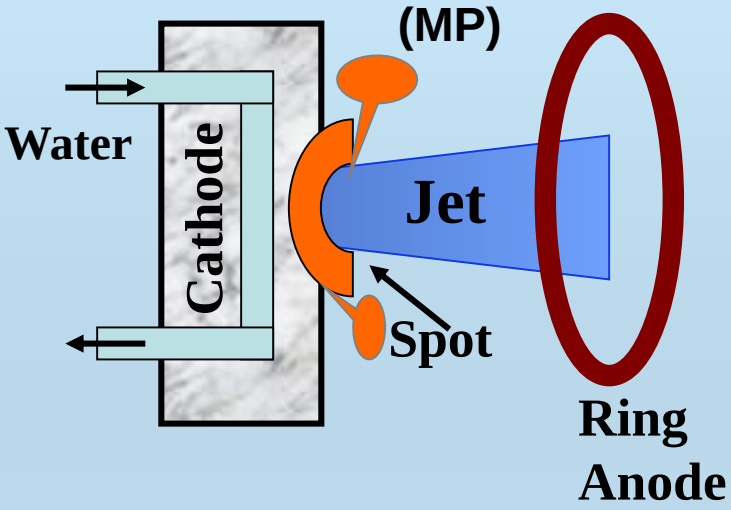
MeVARC-5 2015

Outline

- **Vacuum arc-refractory anode:**
  - **Conventional vacuum arc**
  - **Open cylindrical electrode configuration, HRAVA**
  - **Closed electrode configuration, “Black Body”**
- **Measurements.**
  - **a) Electrode effective voltage**
  - **b) Anode temperature**
  - **c) ion current**
  - **d) Thin film deposition**
- **Summary**

Conventional vacuum arc

V- Arc is low voltage discharge 20-30 V's



Cathode spot, jet:

- Current supported by cathode spots - electron emission and cathode heating
- High local evaporation rate and dense plasma and MP's generation
- Supersonic, fully ionized, high kinetic energy 20-150 eV plasma jet generation
- Different applications including vacuum arc deposition

Effective cathode voltage.

Definition: U_{cef} [V]=Q/I

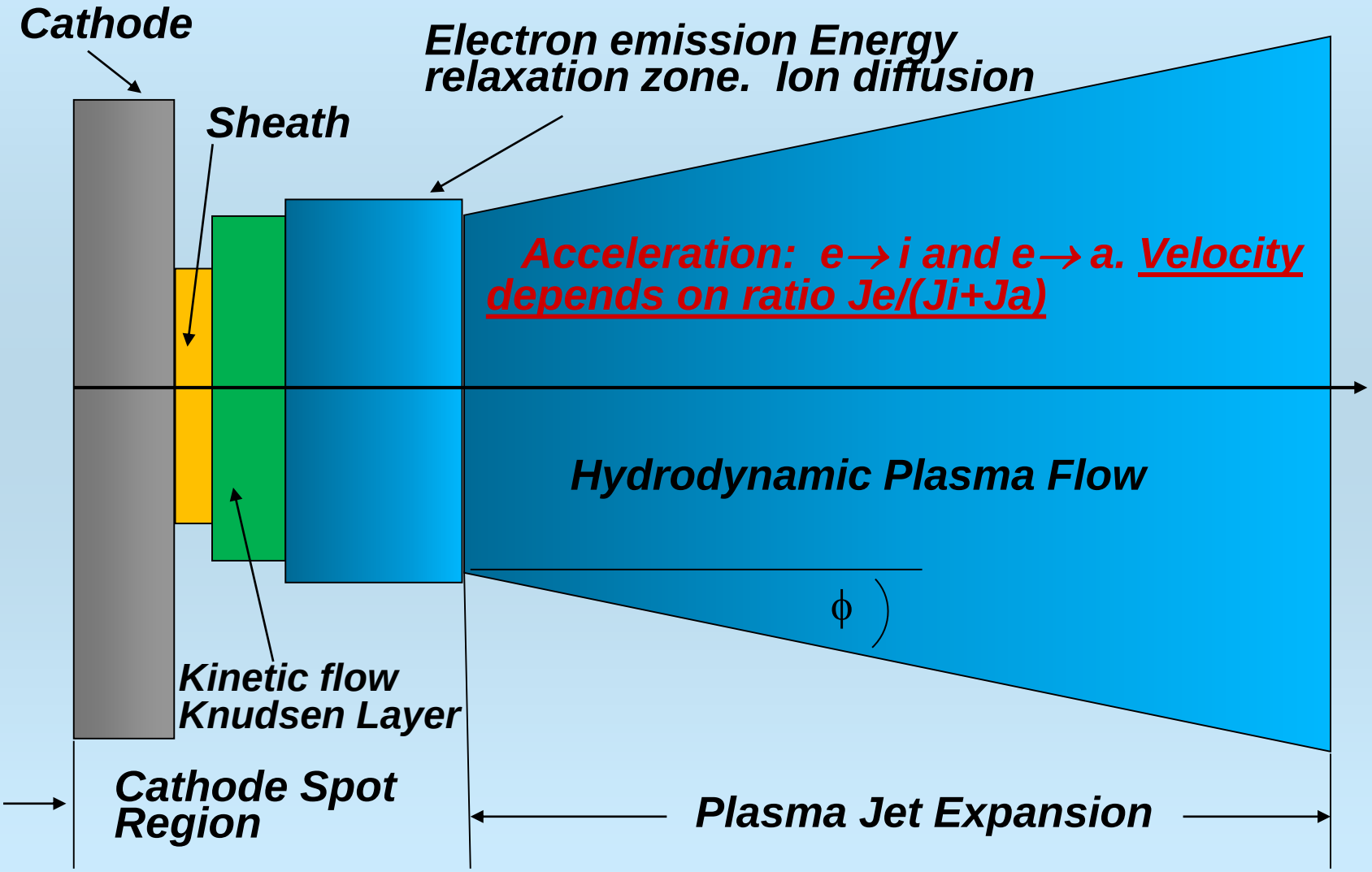
Q –cathode heat flux [W], I [A]

Experiment: U_{cef}=6.2V- Daalder, 1977 (100A)
8V – Reece, 1963 (30A)

Theory: U_{cef}=8V- Beilis, High Temp. 1977

Cathode Spot & Cathode Plasma Jet

Beilis, VAST-1995; IEEE TPS: 1985-2013: APL 2002-2008

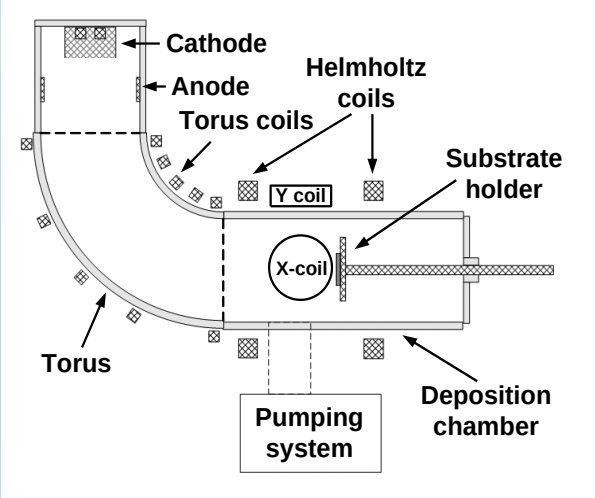


Macroparticle – Plasma cleaning

Deposition Methods

Method	Material	Rate, μm/min
PVD (Magnetron sputtering) IPVD (Ionized PVD)	Ti Al on SiO2	0.017 0.01
CVD	Cu on TiN Cu on Si wafer	0. 05-0.2 0.05-0.1
PACVD (Plasma assisted)	Cu on SiO2, Al	0.004-0.02
SSMD (Self Sputtering)	Cu on Si wafer	0.02-0.4
Electroless	Cu on Si wafer	0.1-0.16
Magnetic Filtered Vacuum Arc Deposition	Cu on glass	0.1

Magnetic Filtered Vacuum Arc

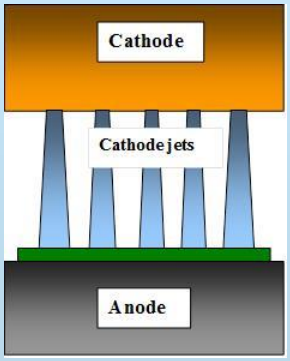


Disadvantages:

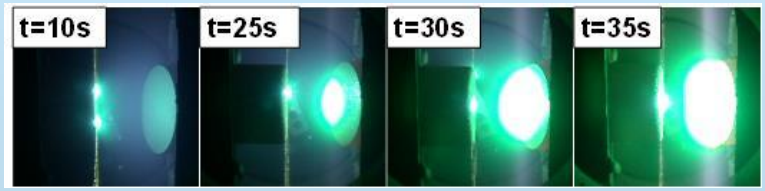
- ***Usually low efficiency of material utilization***
- ***Complex equipment***

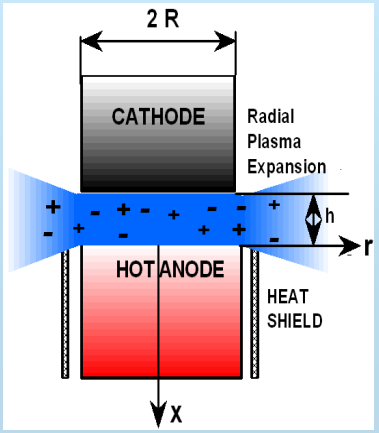
Vacuum arc with Refractory Anode

Hot Refractory Anode Vacuum Arc (HRAVA):



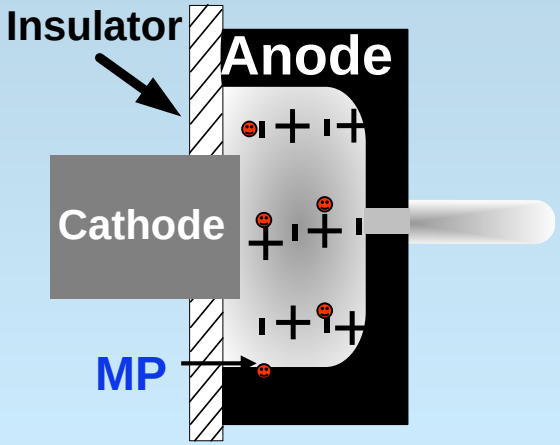
HRAVA development



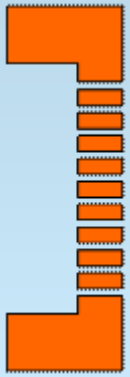


Vacuum Arc with Black Body Assembly (VABBA):

One hole Anode:



Shower Anode:



Vacuum arc with Refractory Anode

Conditions

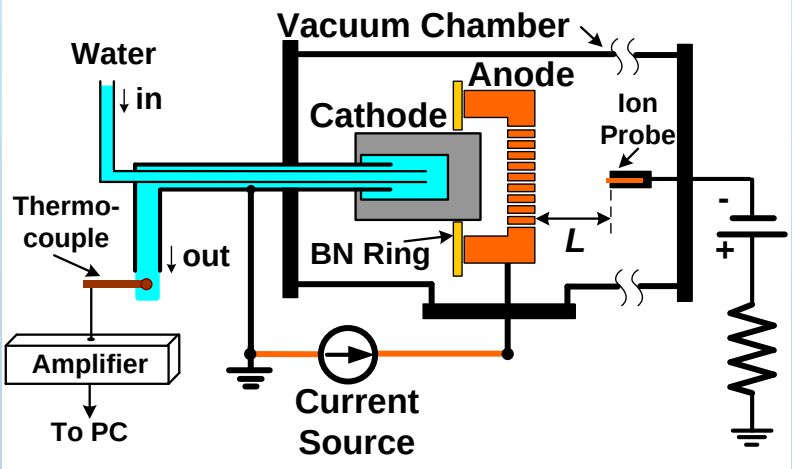
Water cooled Cathode, Gr,Cu, Cr, Ti	Length: 40mm; Diameter: D=30mm
VABBA-Anode	Length: 22mm; D=50mm, W-250 holes (D=1mm) Ta-1 hole, D=4mm
HRAVA Anode A-C distance Anode thickness	W, Mo *h*=5-10mm 5, 10, 20, 30mm
Arc current, *I*	150, 175, 200, 225, 250 A
Arc time, *t*	~180s
W-Thermocouple T-Thermocouple	K-type (chromel-alumel) W/5%Re-W/26%Re
Water flow rate, *F*	0.193, 0.29 L/s
Ion Probe Plasma probe	W rod 1.5mm diameter, V_{bias}=-20V Chamber-total current

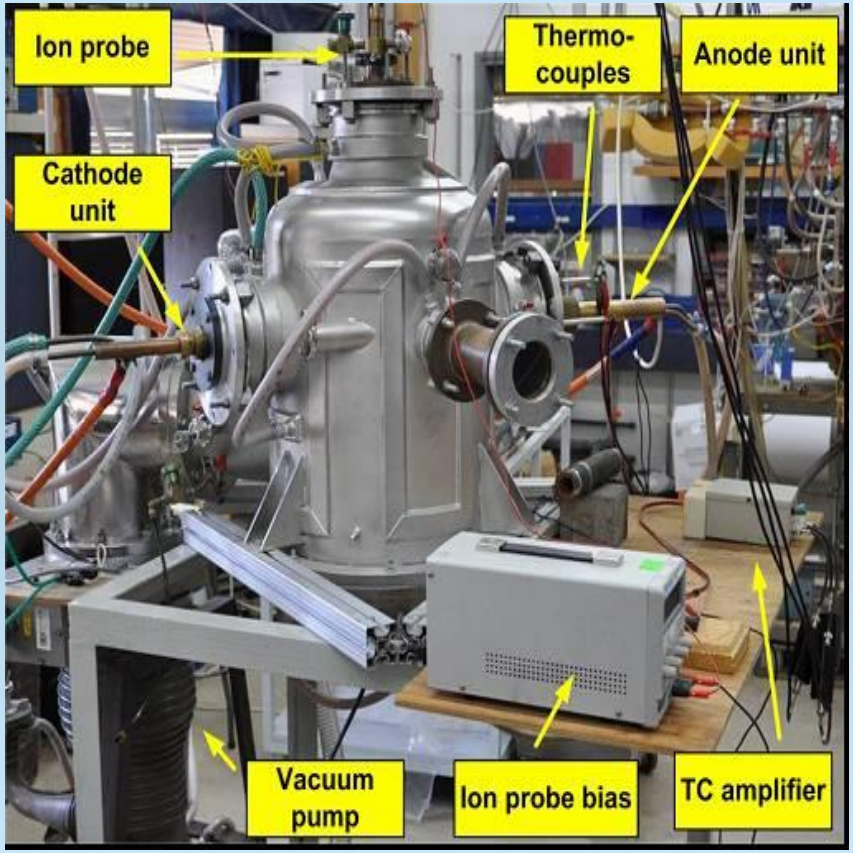
Experimental methodology

- calorimetric test,
- Thermocouple
- Optical Microscopy, SEM
- Photography
- Electrical probe
- Profilometry

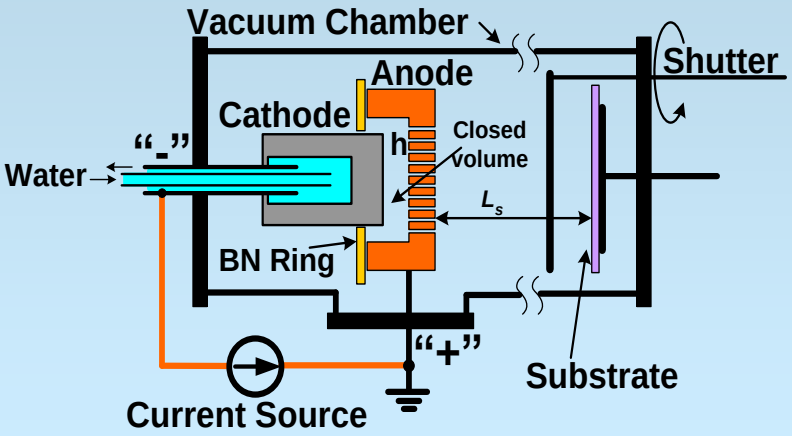
Experimental Setup. VABBA

Calorimetric test. Ion current



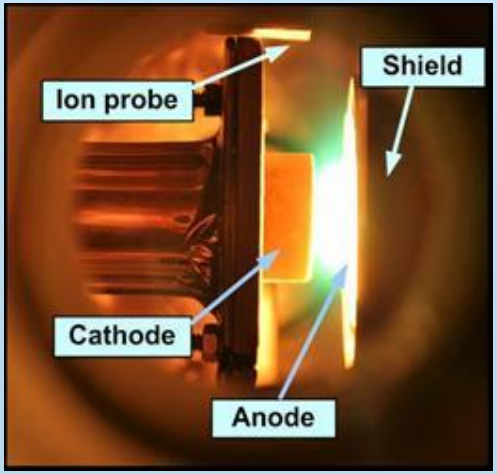


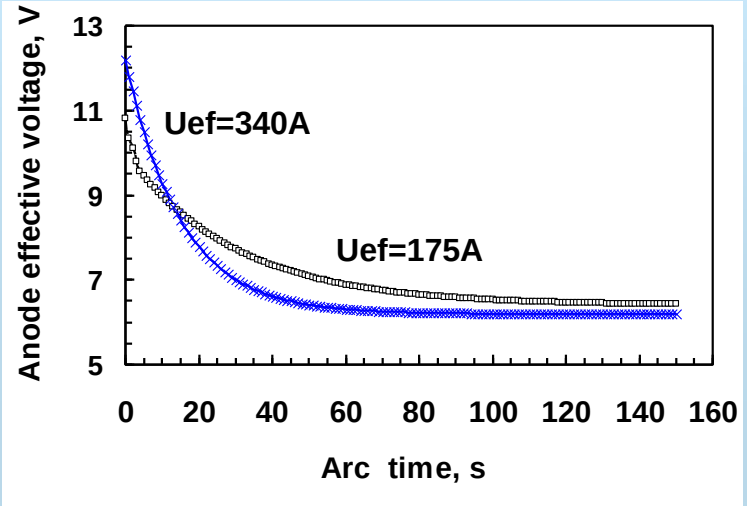
Deposition. Shutter



HRAVA plasma. Effective cathode (Cu) & anode (Gr) voltages

(t>60s)





Cathode: U_{cef}~7V

Anode: U_{aef}~ 11-12V (t<10s)

6.5V (t>60s)

Jet energy IU_j

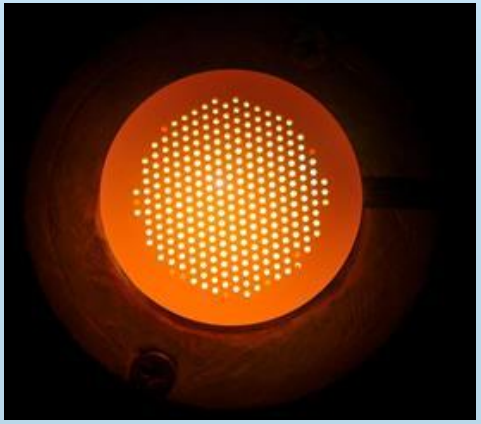
=anode+ surrounding! (t>60s)

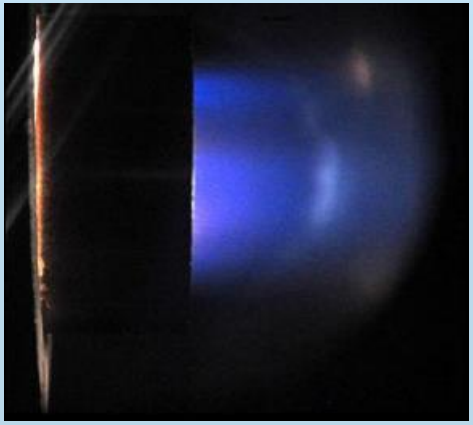
Rosenthal, Beilis, Goldsmith, Boxman, JPhysD 1995

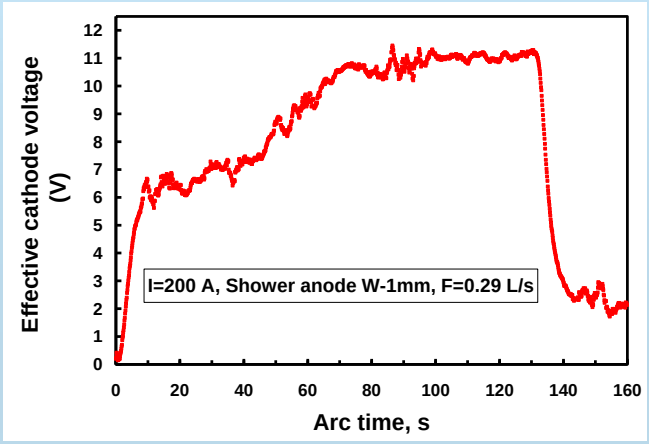
Beilis, Goldsmith, Boxman, PoP 2000 and 2002

VABBA plasma and effective cathode voltage

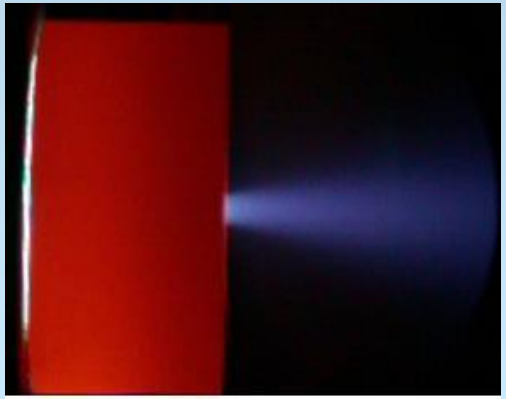
Shower W Anode, 250 holes-1mm:



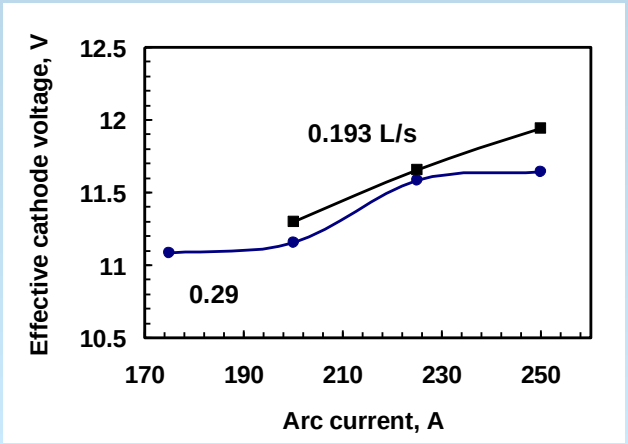




One hole (4mm) Ta Anode:



$$U_{cef} = \frac{c_p \Delta T \rho_w F}{I}$$



U_{cef} (VABBA)=11-12V consists of:

1) U_{cef} = 6.5V (conventional from the spot) and

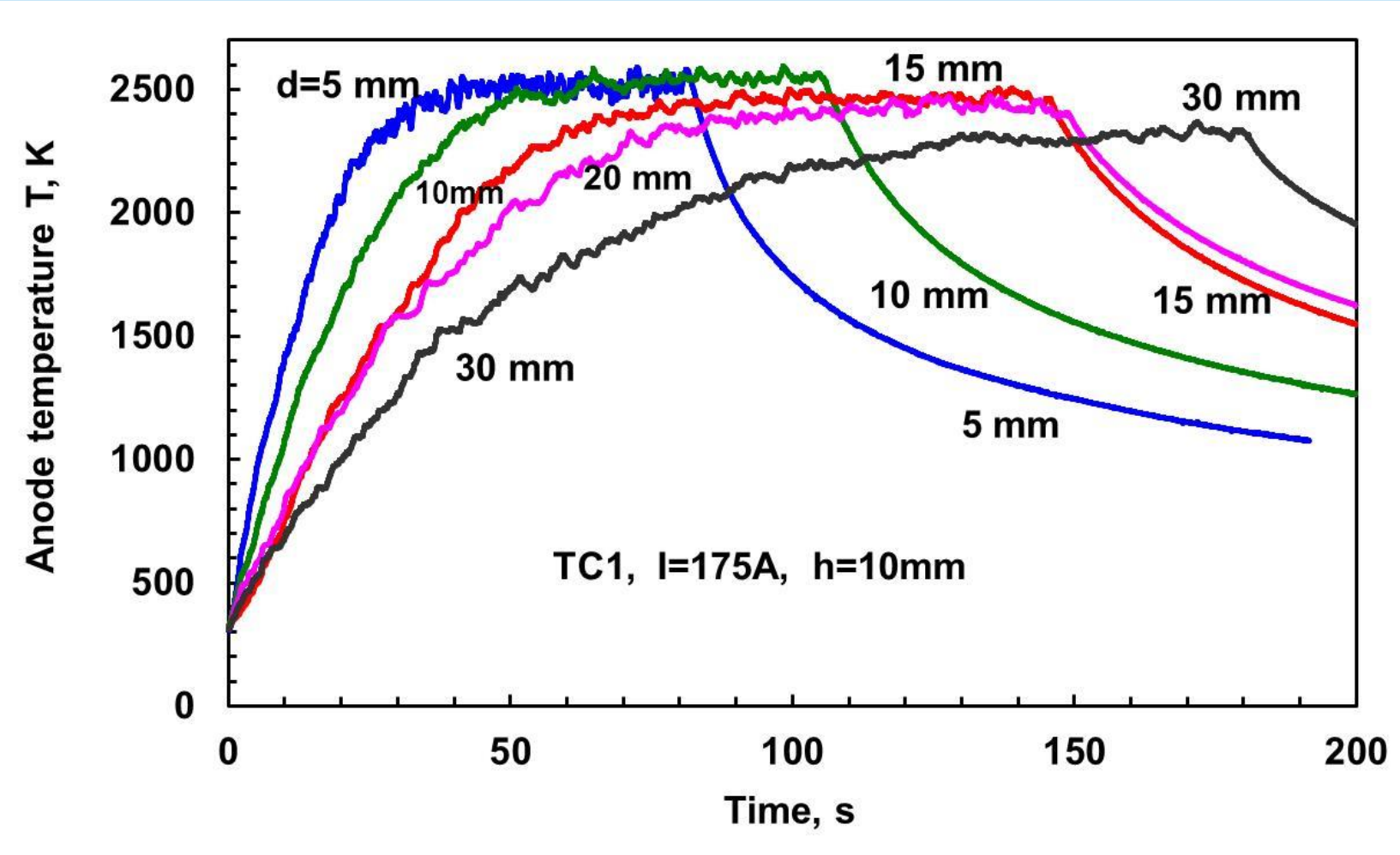
2) part of returned plasma jet energy *U_j (12V)*

***that not expands to surroundings and remains in the closed electrode configuration*!**

IEEE Trans. Plasma Sci., 41, N8, Part II, 1992, 2013

W Anode surface temperature vs. time with anode thickness as parameter (HRAVA)

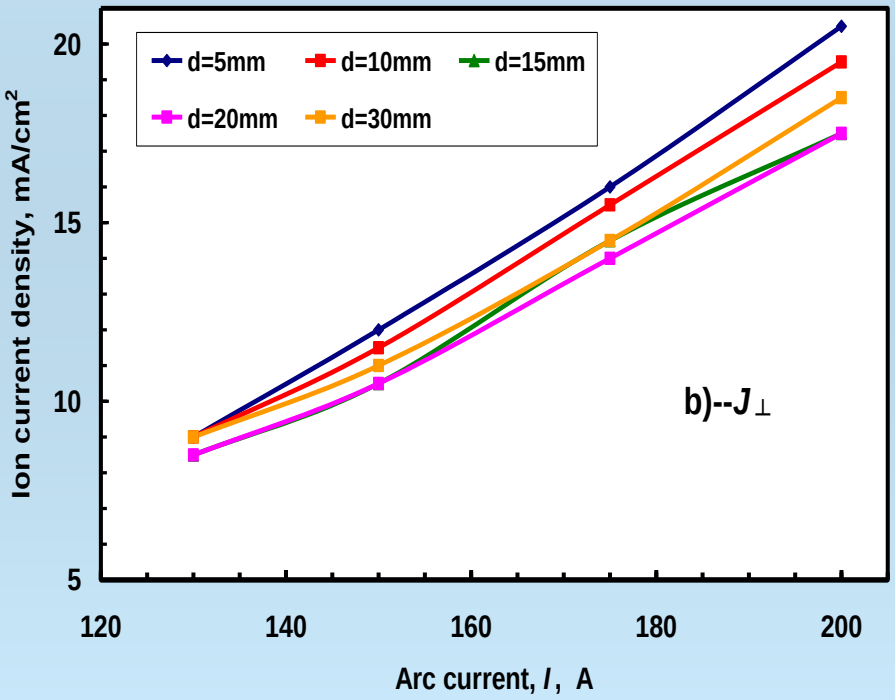
IEEE Trans. Plasma Sci., 39, N6, Part I, 1307, 2011



Ion current (HRAVA)

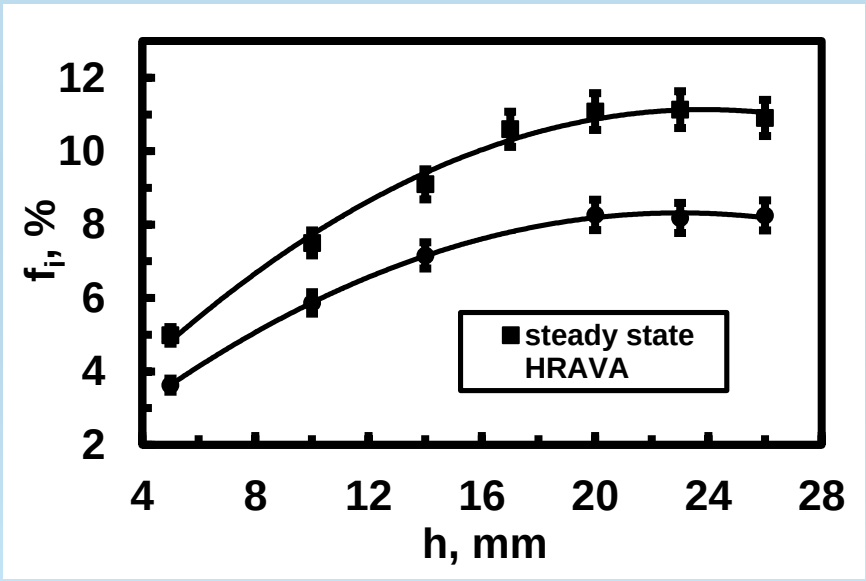
Ion current as function of arc current h=10mm

J. Appl. Phys., 111, Part I, 043302, 2012



Ion current fraction f_i as function on gap I=200A

Appl. Phys. Lett. 88, 071501, 2006



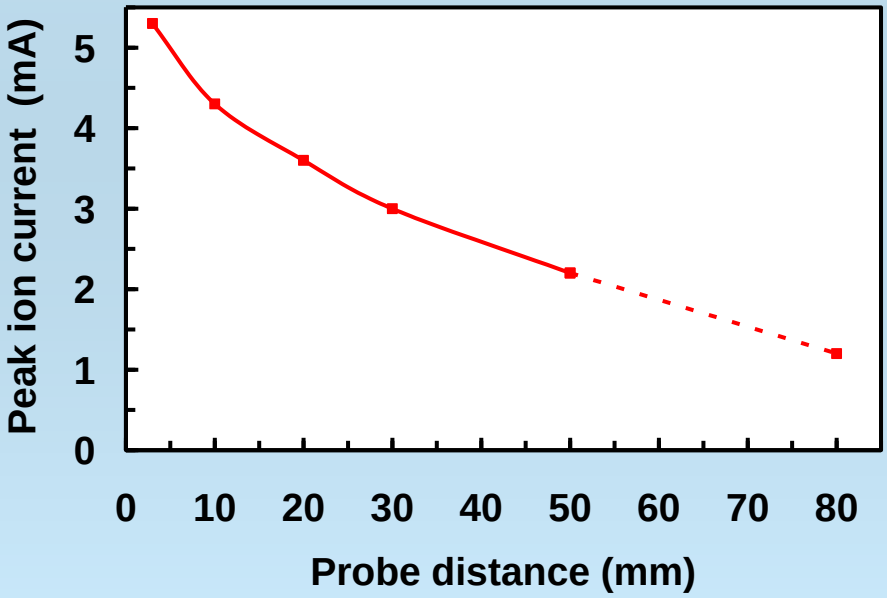
- ● ***--at first few seconds (8%)***
- ■ ***--at steady state (11%)***

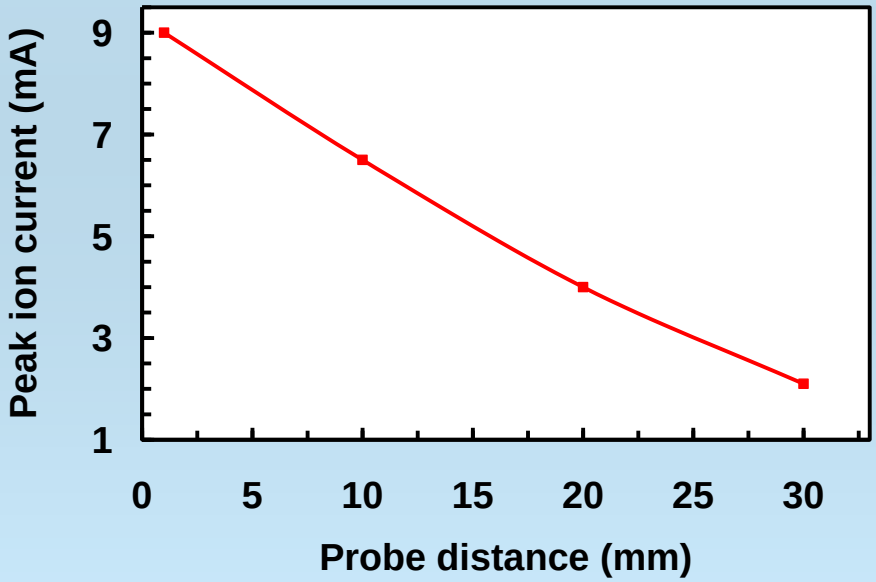
Ion current dependence on probe distance L, Cu, I=200A (VABBA)

W shower anode
250 holes, 1mm diameter

Ta anode with one hole
(4mm diameter)

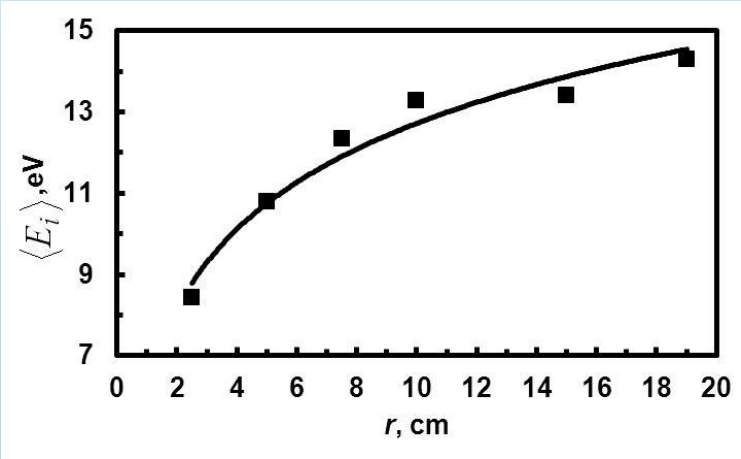
IEEE Trans. Plasma Sci., 41, N8, Part II, 1987, 2013





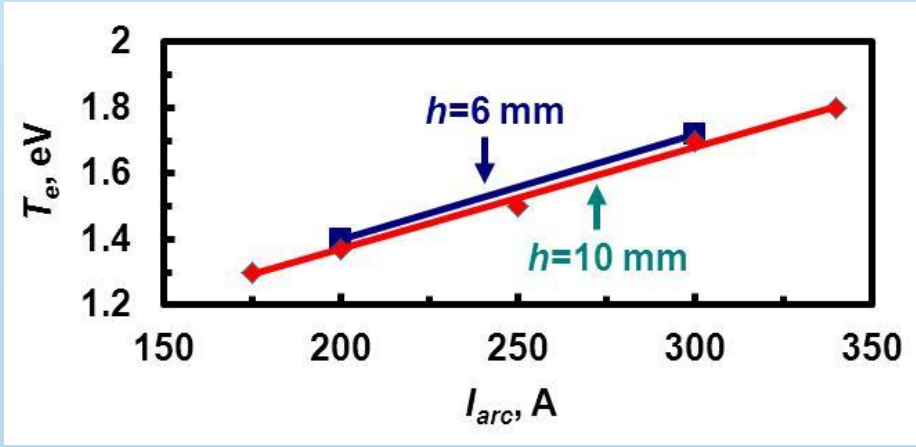
Plasma parameters, HRAVA

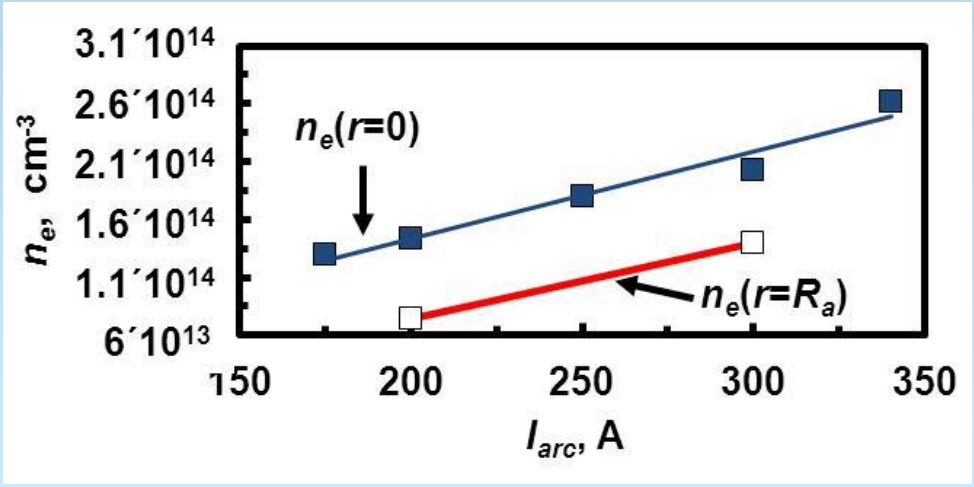
Ion energy E_i vs. distance
I=200 A, h = 10 mm.



Plasma temperature vs. I

Plasma Sour. Sci. & Techn., 18 (2009) 045004

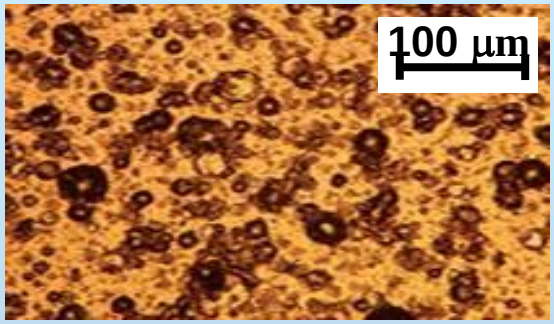




Plasma density vs. I

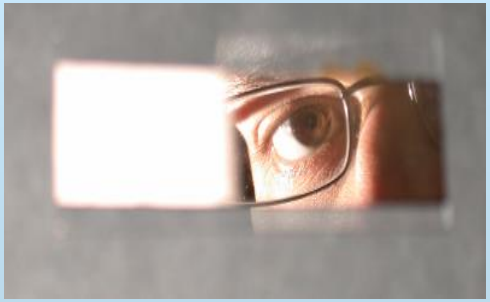
Metallic film deposition, W anode

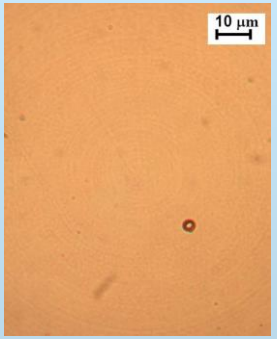
Surf. &Coat. Techn., 203, Is.5-7, 501, 2008



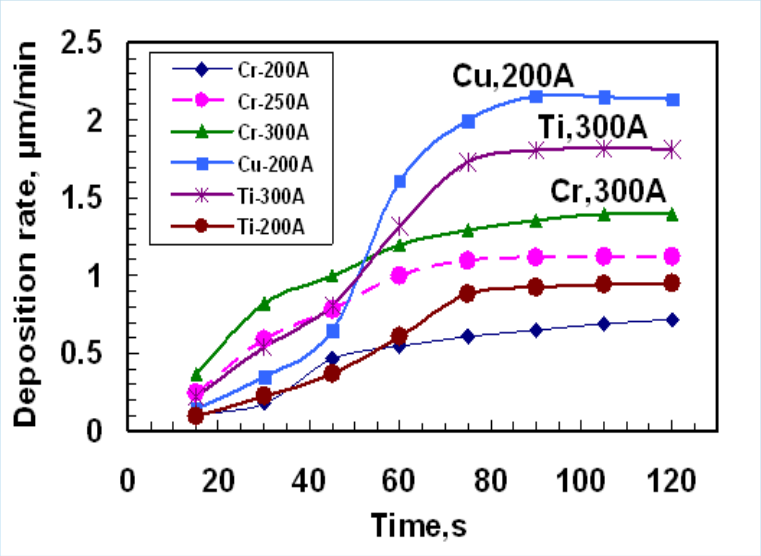
Conventional Arc

Refractory anode





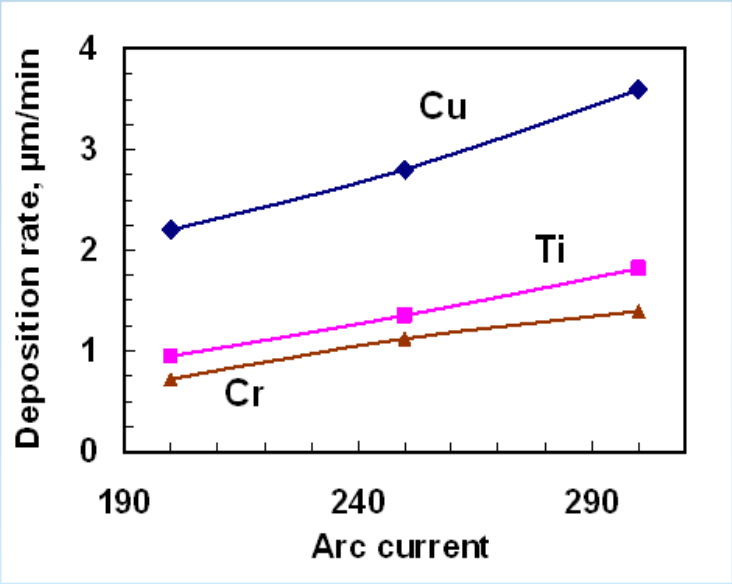
Temporal evolution (HRAVA)



Glass substrate h=10mm

Shutter open for 15s

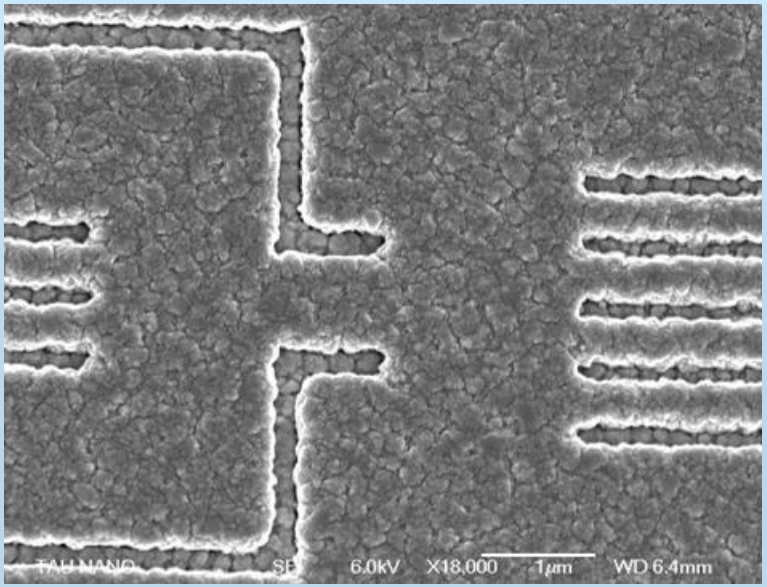
Dependence on current, A

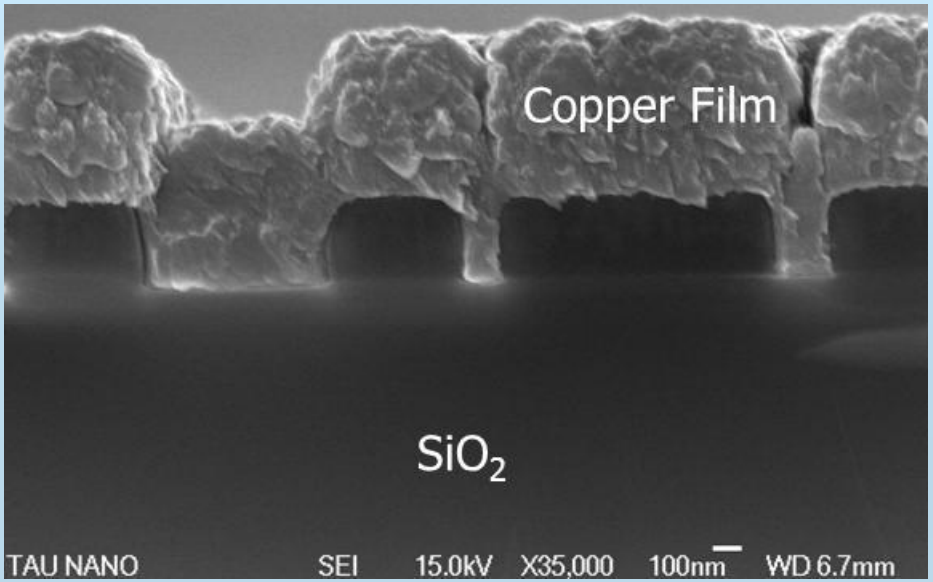


At *L*=80mm: *Cr* , *I*=200, 250, 300A,
Cu, *I*=200A

At *L*=100mm: *Ti*, *I*=200 and 300A

Microelectronics
Trenches filling by Cu, HRAVA





100 nm wide × 300 nm deep

Microelectronic Engineering, 85 ,1713, 2008

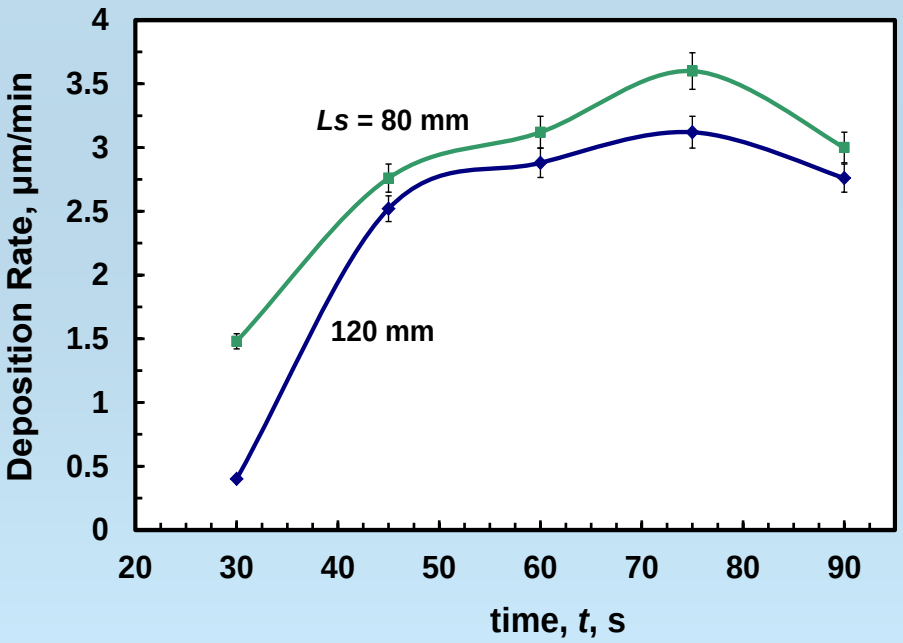
The deposition rate was ~0.5 μm/min.

Film deposited with 2 min exposure at a distance of 110 mm, using pulsed biasing with amplitude -100 V, 80% duty cycle and a frequency of 60 KHz.

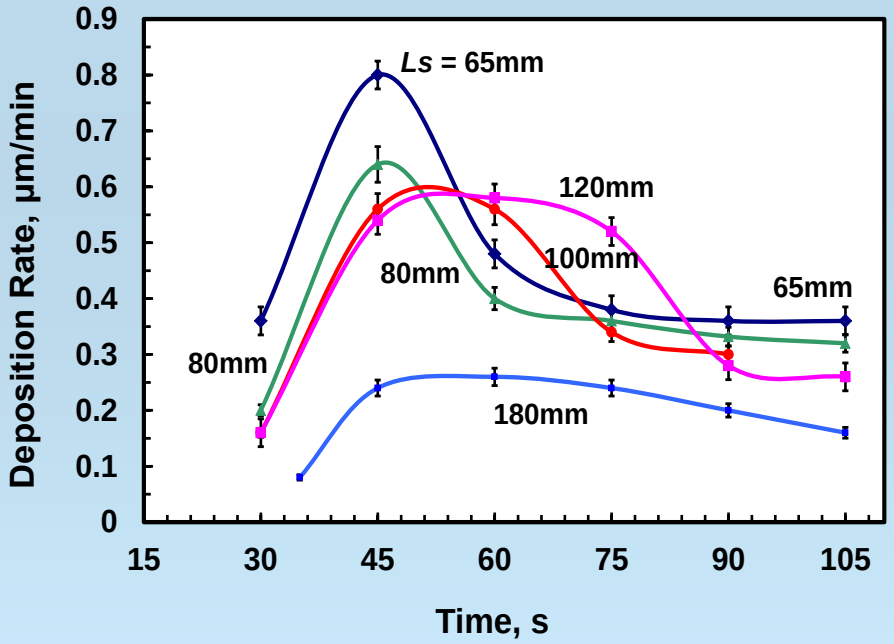
Cu deposition rate on glass, h=10mm, VABBA

Surf. &Coat. Techn., 258, 908, 2014

W shower anode
(250 holes, 1mm), 200A



Ta shower anode
(250 holes, 0.6mm), 200A



SUMMARY

- The refractory anode arc characterized by plasma plume expanding radially (HRAVA) or directly (VABBA) . Plasma – is the cathode material!
- *Cathode* U_{cef} in VABBA increases to ~6.5 V for cold anodes (like conventional cathodic arc) & then to steady state of ~11-12 V after anode is heated
- The ion flux fraction (12%) in arc with refractory anode was larger in comparison to conventional arc (8%)
- Plasma temperature was T_e~1.3-1.8eV, density>10^{14}cm^{-3}, and plasma was accelerated up to ~15 eV during its expansion.
- The arc is a simple metallic plasma source for coatings. The high efficiency is determined by MP's conversion into plasma
- Steady-state HRAVA deposition rate reach 3.6(Cu), 1.8(Ti) and 1.4μm/min (Cr) for *I*=300A, while PVD, CVD, FVAD showed about 0.1μm/min (Review: Surf. & Coat. Techn., 204, N6-7, 865, 2009).

Thanks to our colleagues:

- **Samuel Goldsmith**
- **Michael Keidar**
- **Alexey Shashurin**
- **David Arbilly**
- **Arye Snaiderman**
- **Dmitry Grach.**
- **Yosef Koulik**

Thank You