Marks on Single-Crystal Copper Cathodes after Short-Pulse Voltage Impact on Vacuum Gaps

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The work was supported by the Russian Foundation for Basic Research, Project No. 18-08-00230-A.

Introduction

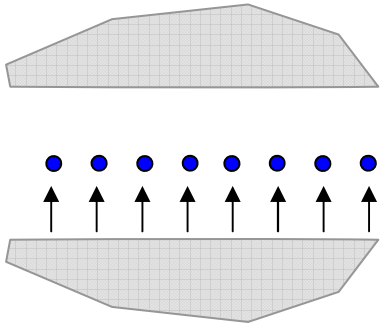
- Theoretical electric strength of vacuum insulation E_{lim} ~ 3 GV/m

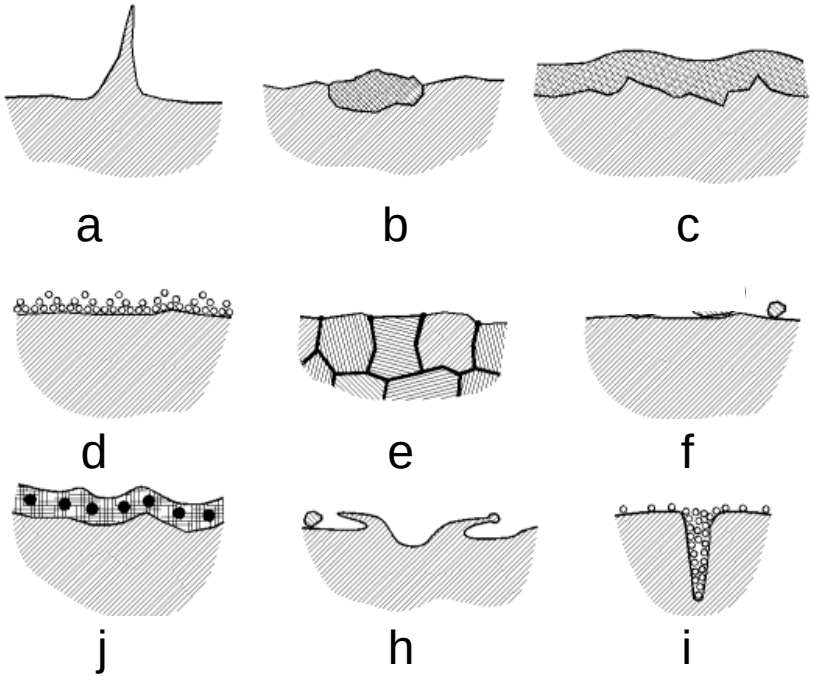
- Real electric strength of mm-cm vacuum gaps (VG) E_{br} < 0.1 GV/m

- Various types of inhomogeneities that lead to breakdown of VGs:

- (a) – micro-protrusions;
- (b) – dielectric inclusions;
- (c) – oxide films;
- (d) – layers of adsorbed gas;
- (e) – outcrops of intergranular boundaries;
- (f) – polyatomic particles;
- (g) – products of oil vapors;
- (h) – edges of craters formed as a result of previous breakdowns;
- (i) – pores and cracks.

Ideal electrodes





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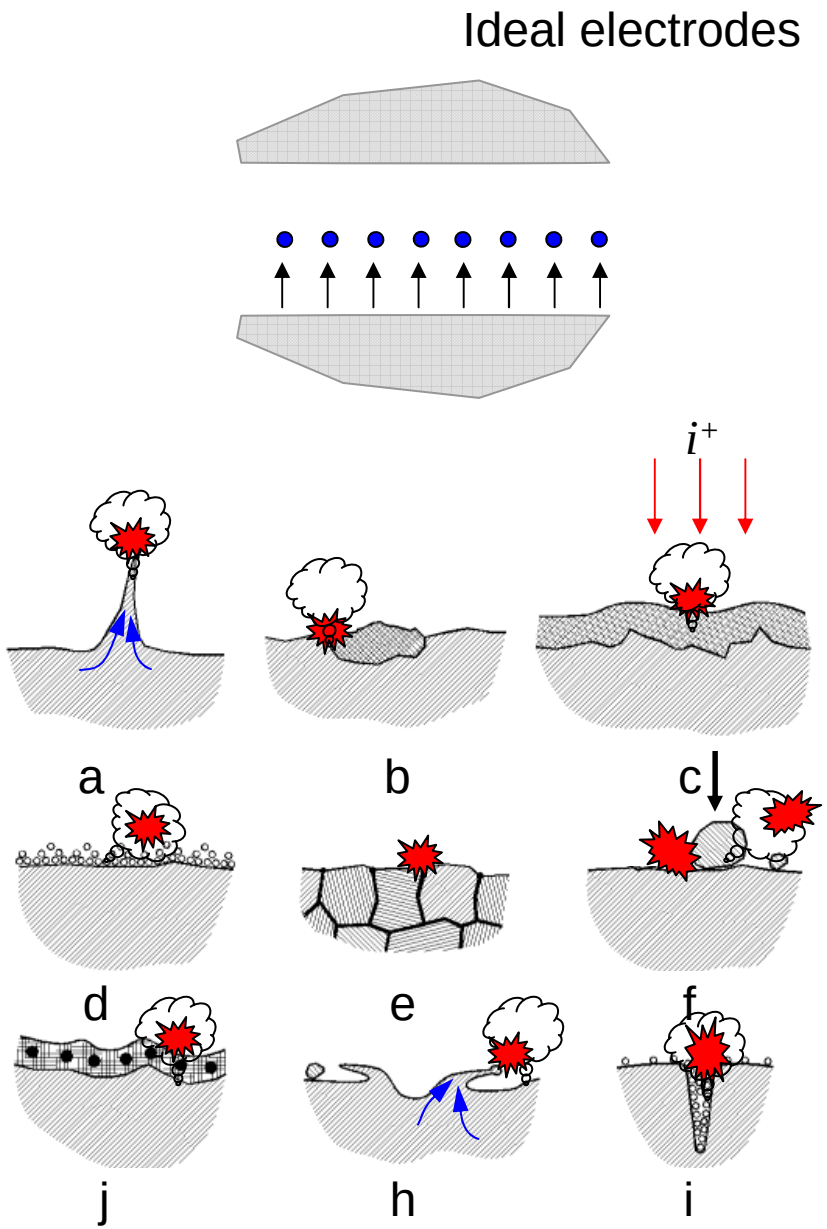
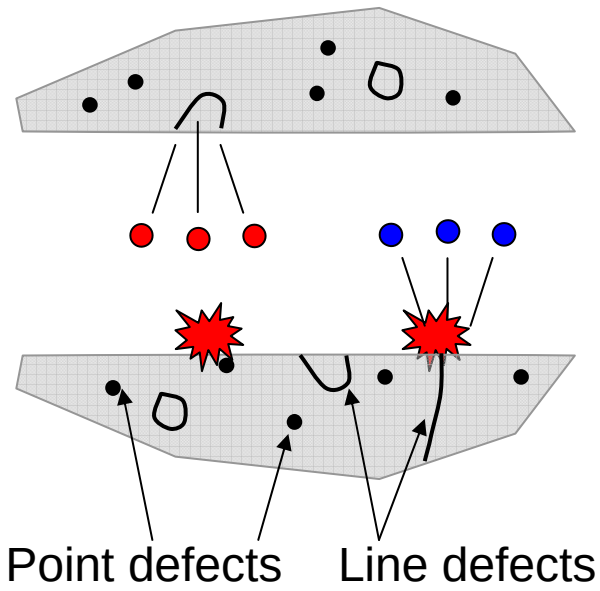


Introduction

Modern methods of surface cleaning allow to exclude explicit micron and submicron inhomogeneities from electrodes surface.

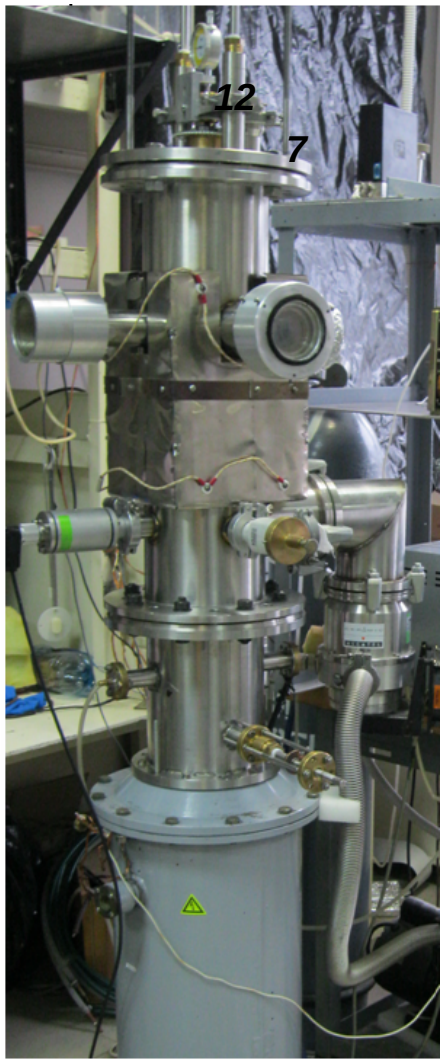
Therefore today, the search for factors of violation of electrical strength of VGs shifts to the atomic scales. Recent theories indicate that the initiators of the vacuum breakdown may be defects of crystal structure of electrode material, most likely the dislocations.

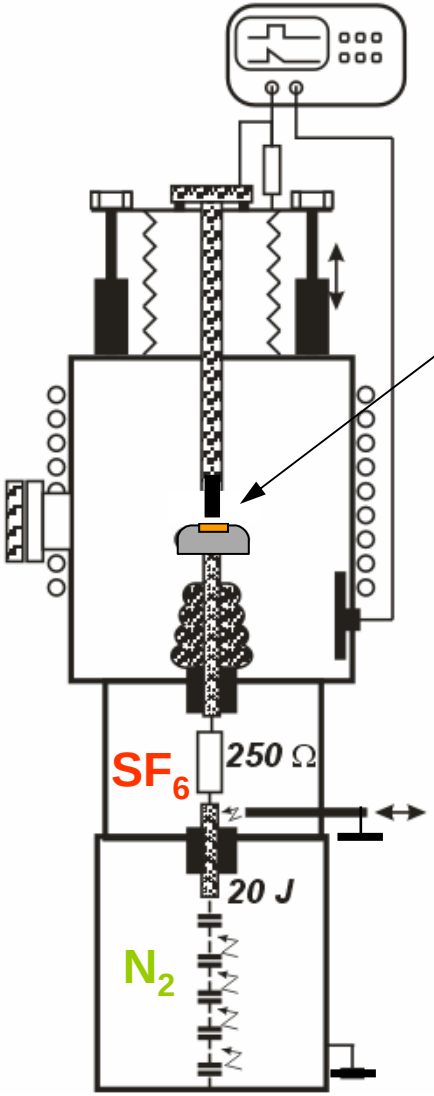
Electrodes with lattice defects

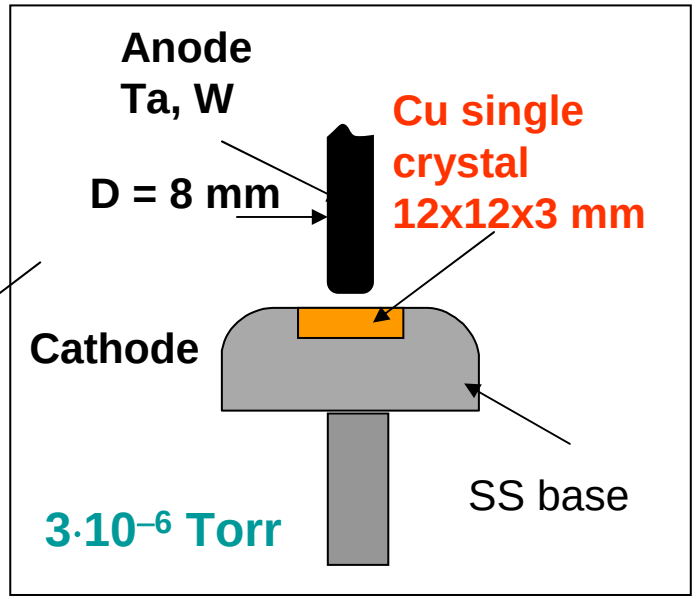


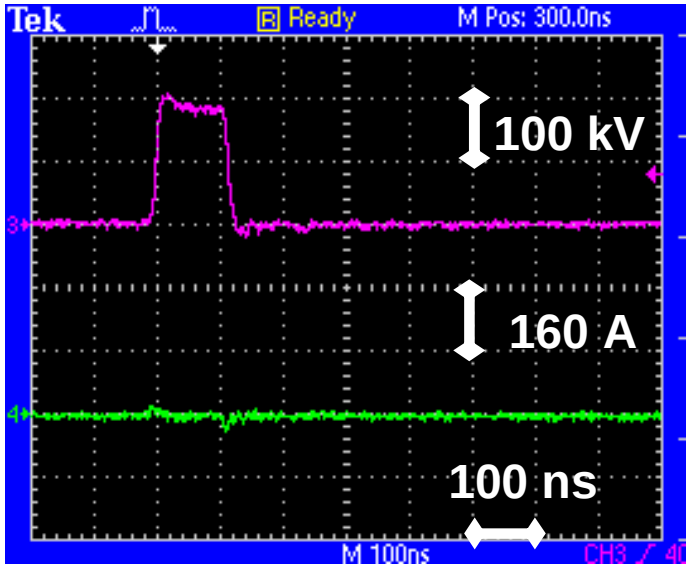
- K. Nordlund and F. Djurabekova, *Phys. Rev. Accel. Beams,* vol. 15, pp. 071002 (1-7), 2012.
- E. Z. Engelberg, A. B. Yashar, Y. Ashkenazy, M. Assaf, and I. Popov. *Phys. Rev. Accel. Beams,* vol..22, pp. 083501-(1-16), 2019.
- A. Saressalo, A. Kyritsakis , F. Djurabekova, I. Profatilova , J. Pasz-kiewicz , S. Calatroni , and W. Wuensch. *Phys. Rev. Accel. Beams*, vol. 23, pp. 023101 (1–11), 2020.

Experimental stand 1









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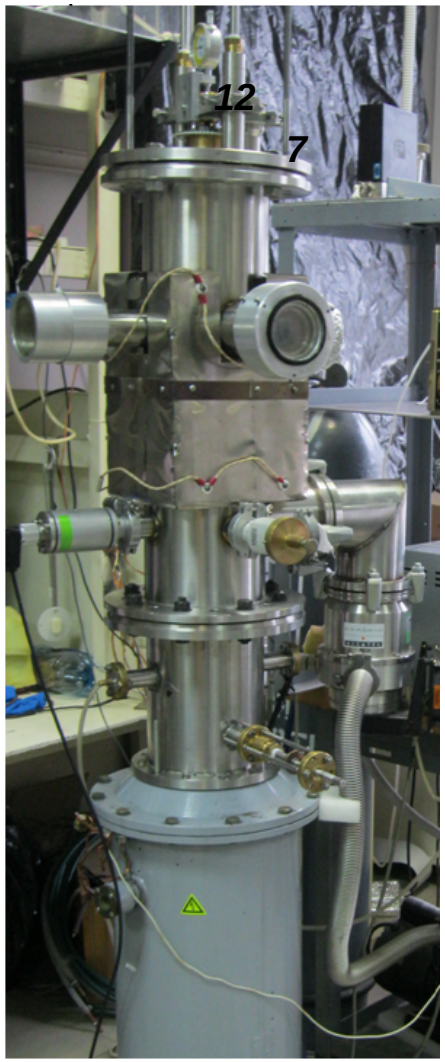

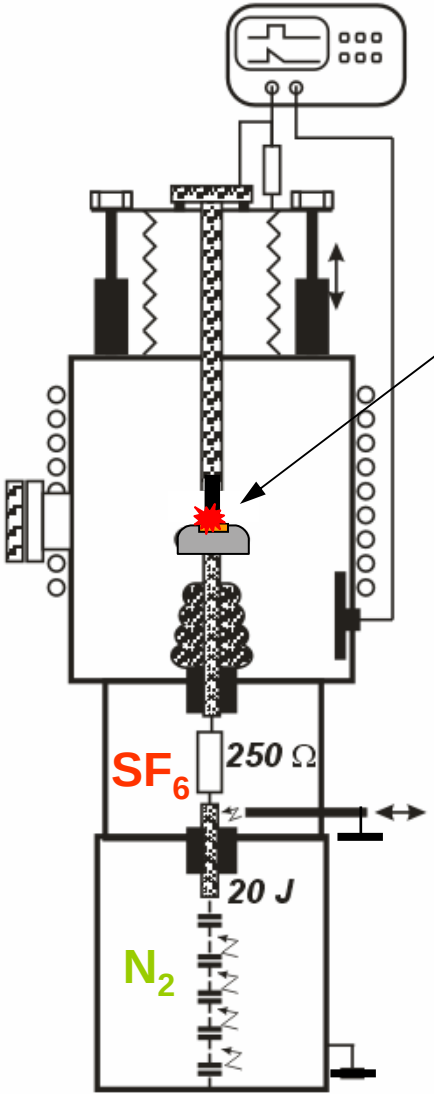

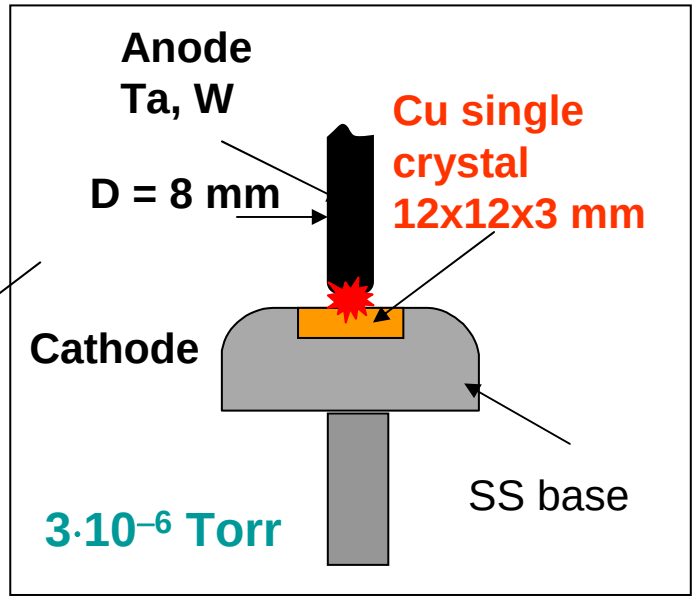

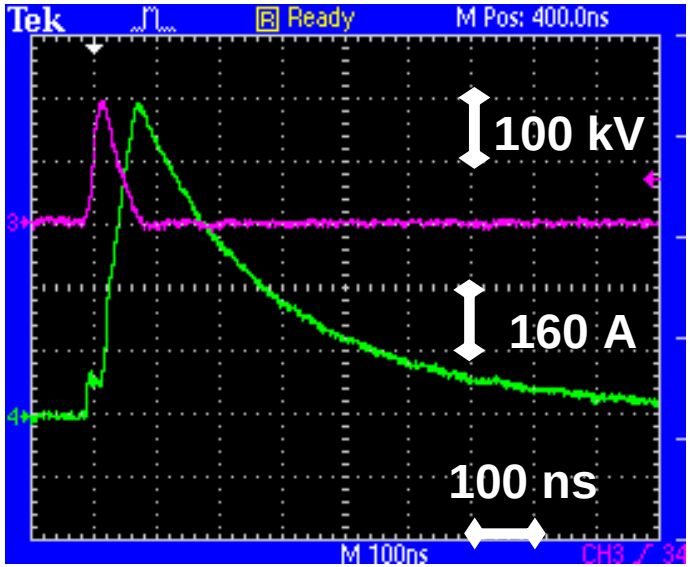

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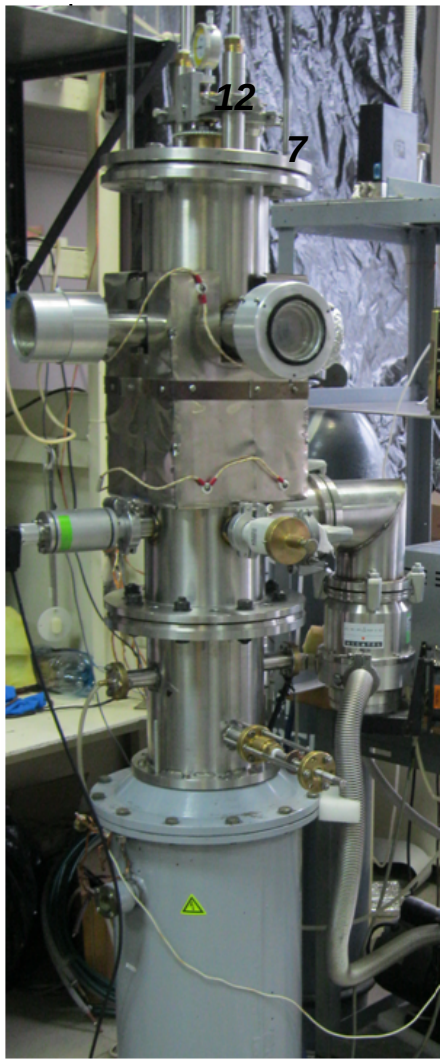
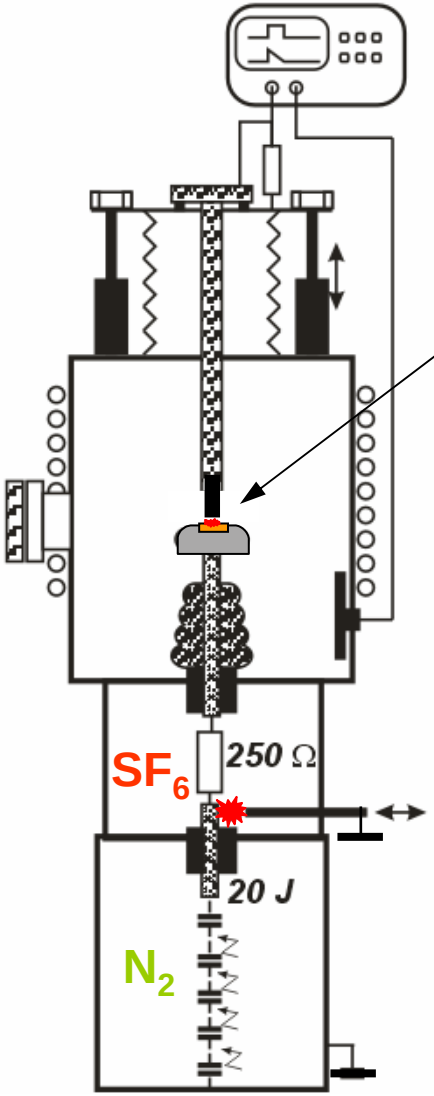
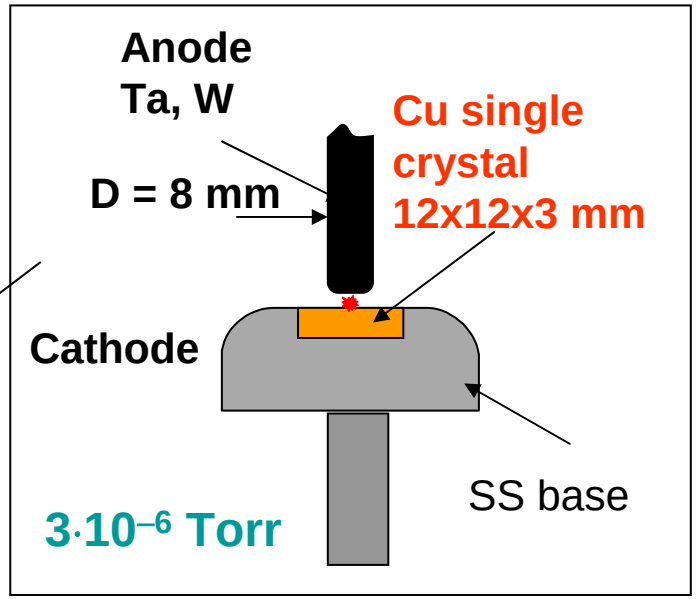
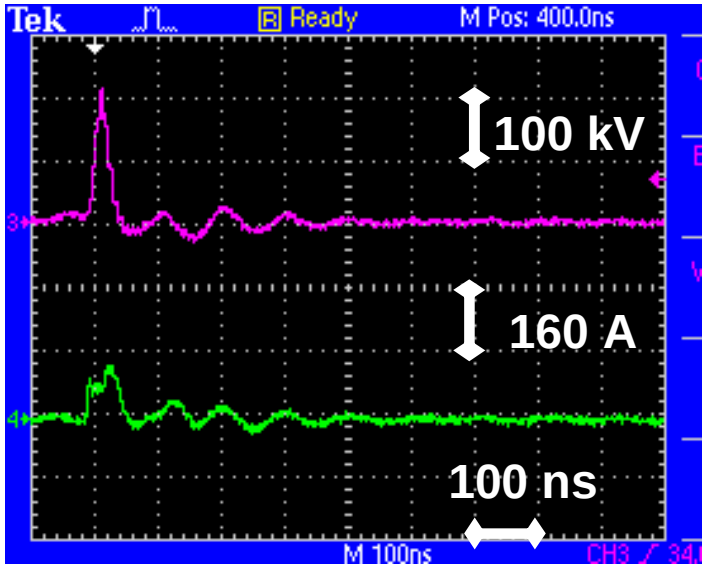
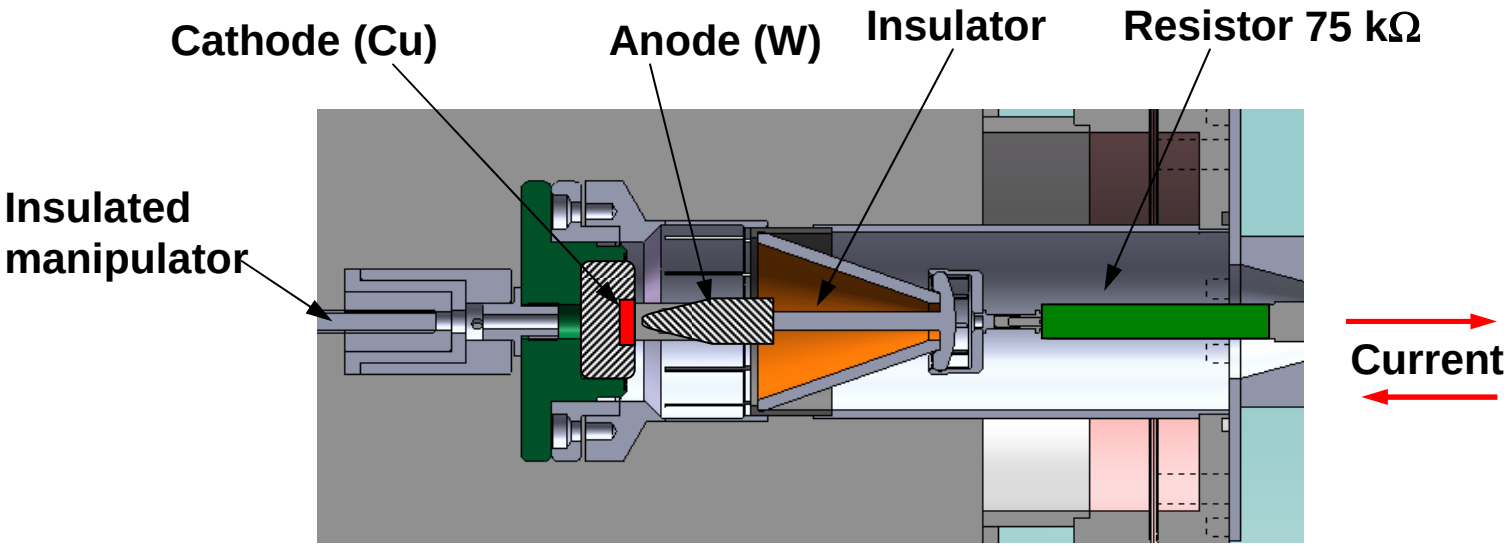


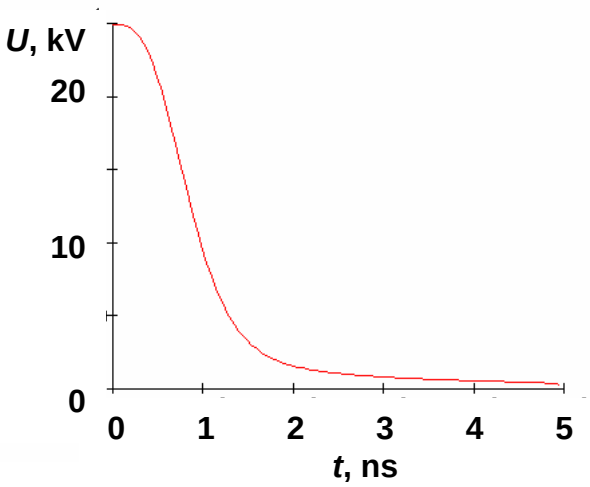


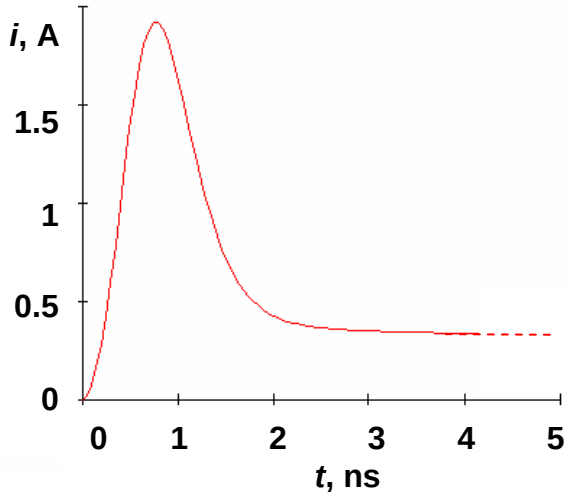




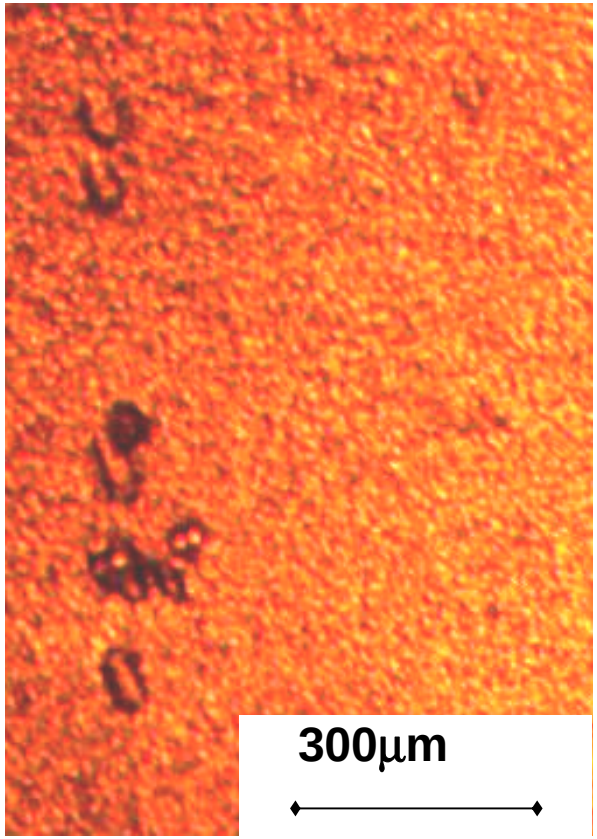
Experimental stand 2

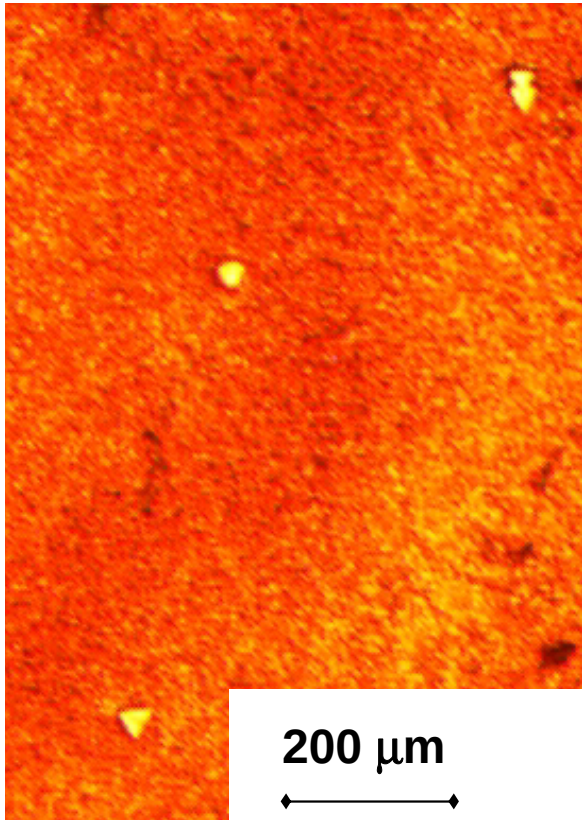






Etching pits on dislocations outcrops



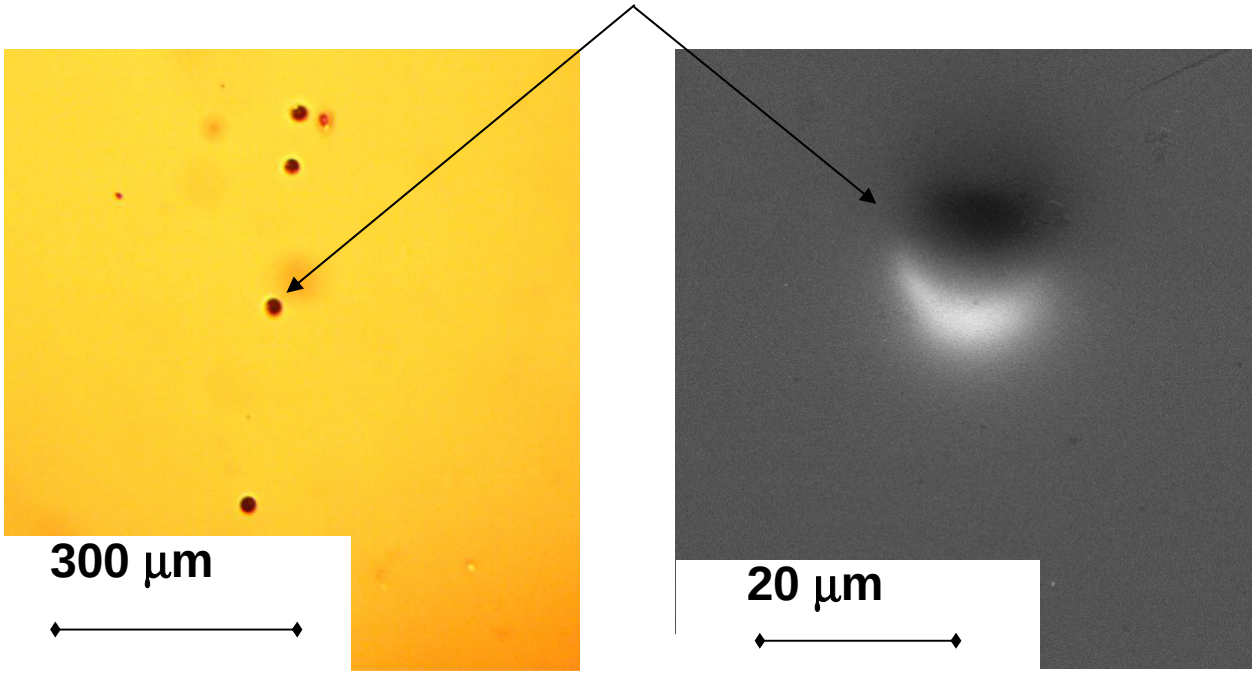


surface (110) **surface (111)**

(10 gm $(NH_4)_2S_2O_8$ + 10 ml H_2O_2 + 50 ml H_2O)

Electrolytic polishing of copper surface (state before vacuum spark)

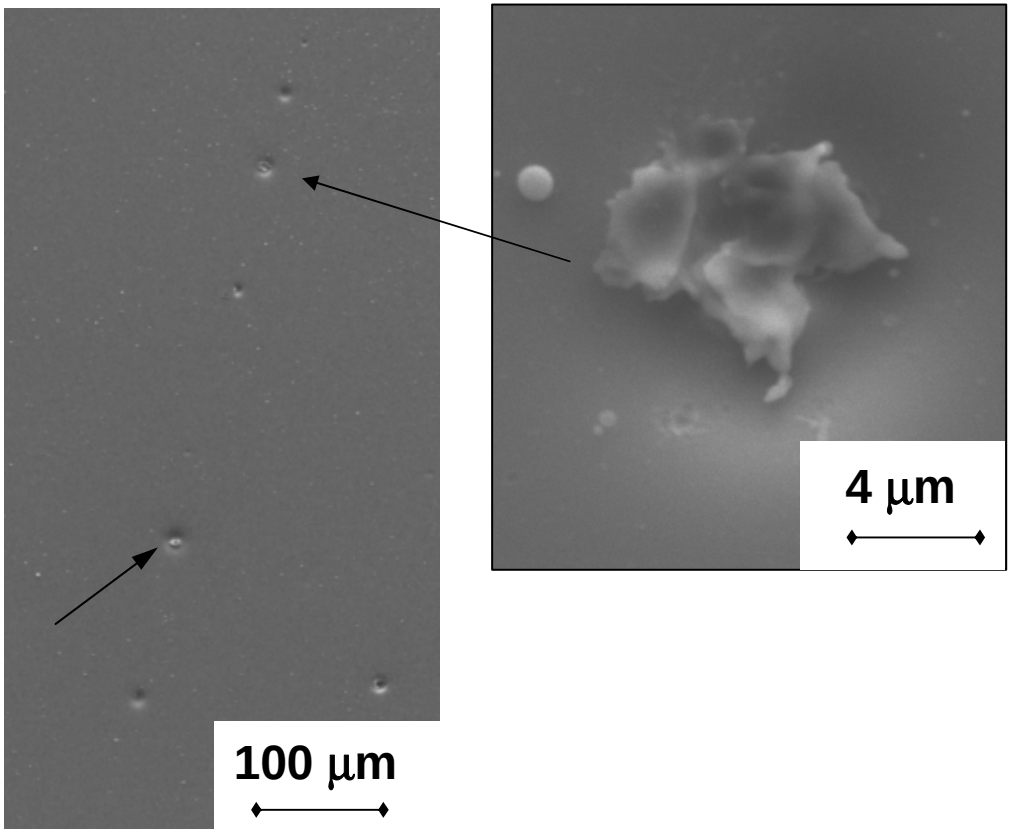
Marks of dislocations outcrops after polishing



Optical image **Electronic image**

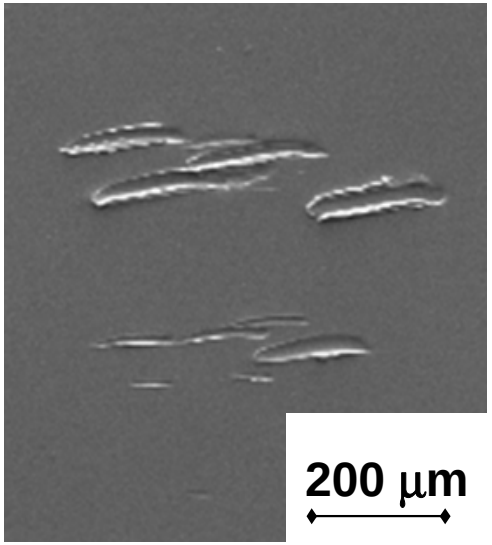
H_3PO_4 saturated with Cu^{2+} ions

Marks after “high current” treatment

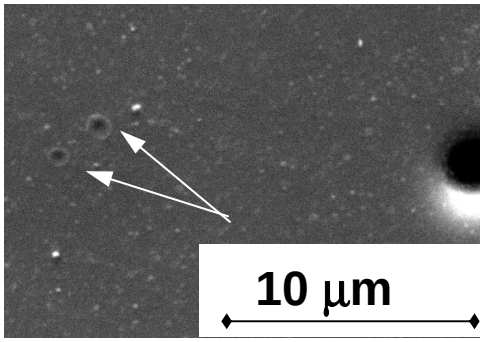


Micron erosion centers

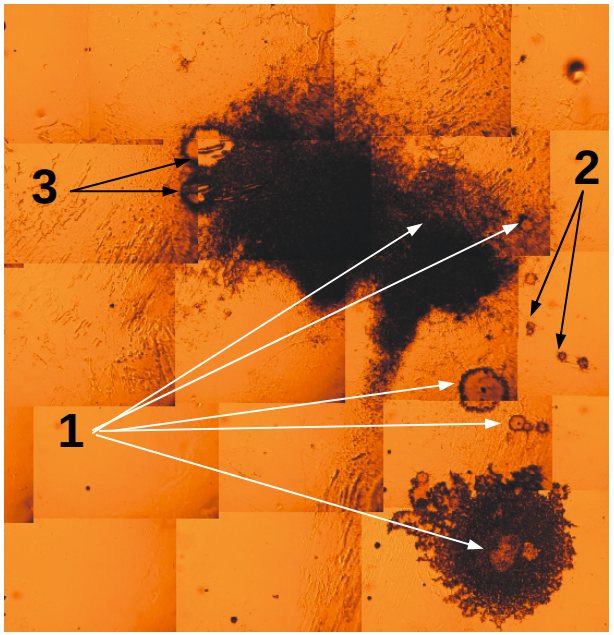
“Strokes"

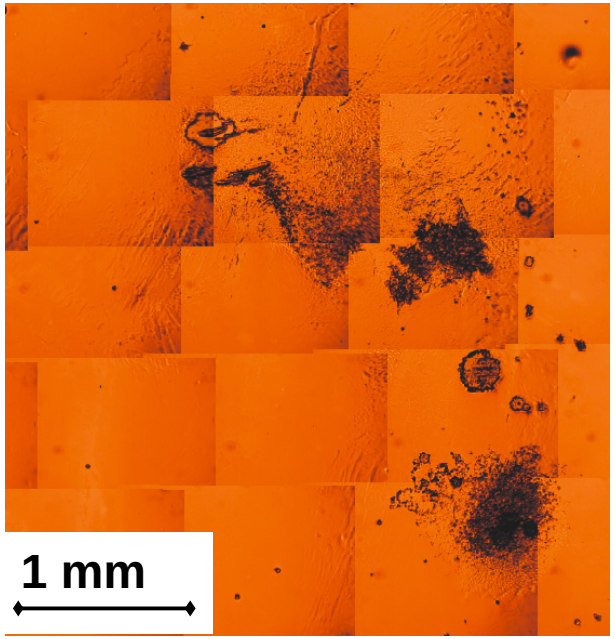


Submicron erosion centers



Etching after “high current” treatment





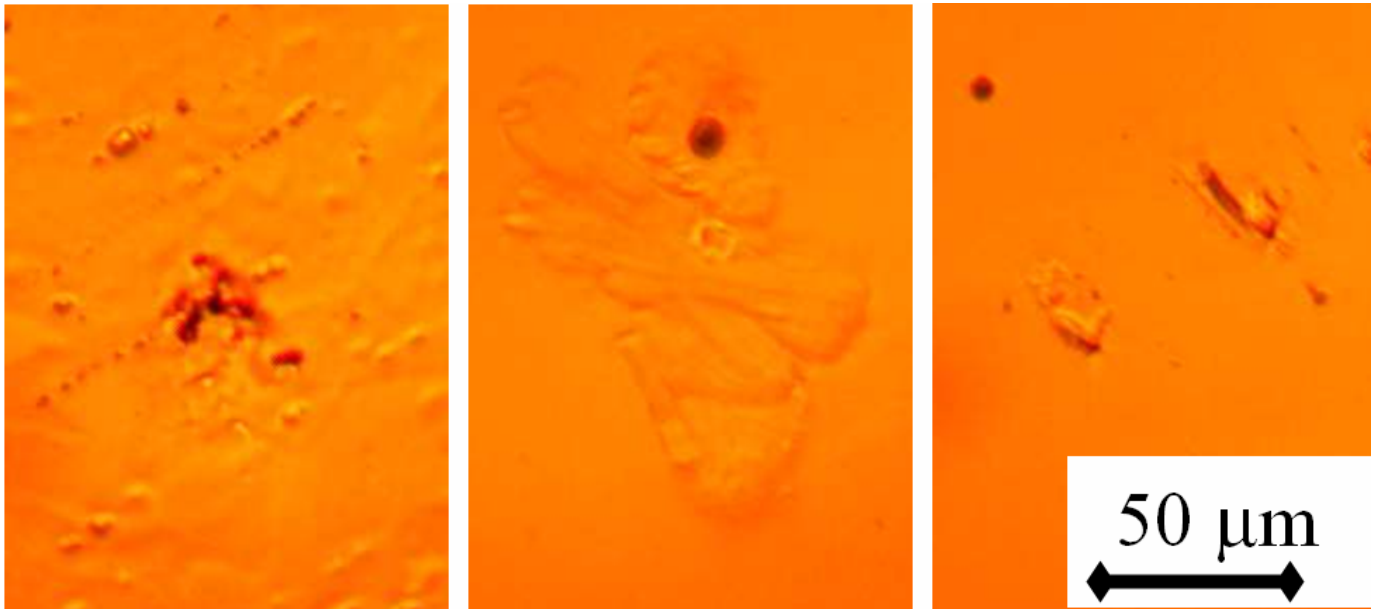
1 min

10 min

Spark traces which revealed by etching :

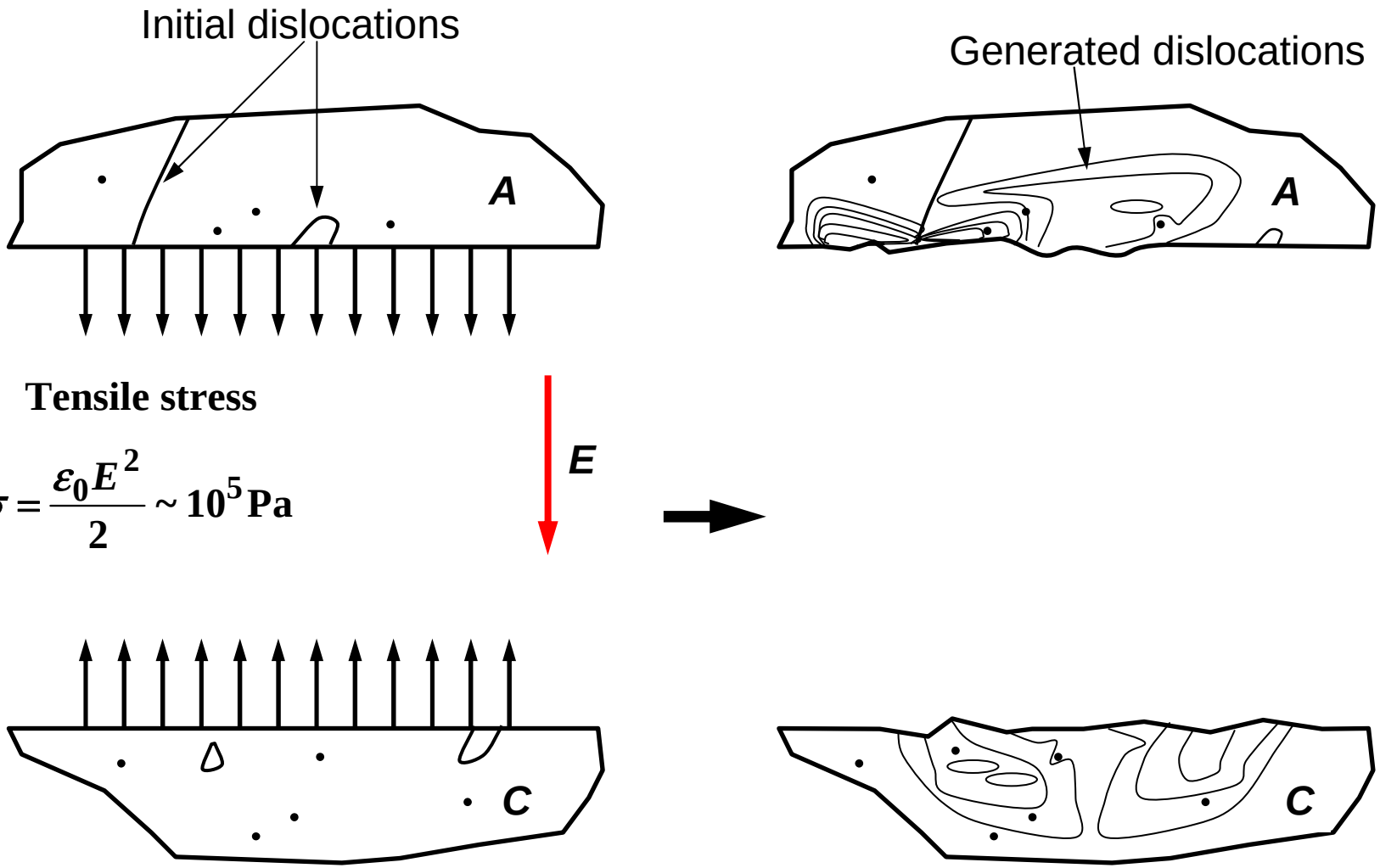
1 - erosion centers which coincided with original dislocations
2 - submicron erosion centers,
3 - "strokes".

Marks after “low current” treatment



Polycrystalline (with etching) **(110) surface** **(111) surface**

Discussion



Tensile stress

$$\sigma = \frac{\varepsilon_0 E^2}{2} \sim 10^5 \text{ Pa}$$

Yield strength of metals ~ 10^7 Pa

Discussion

What do we know about dislocations?

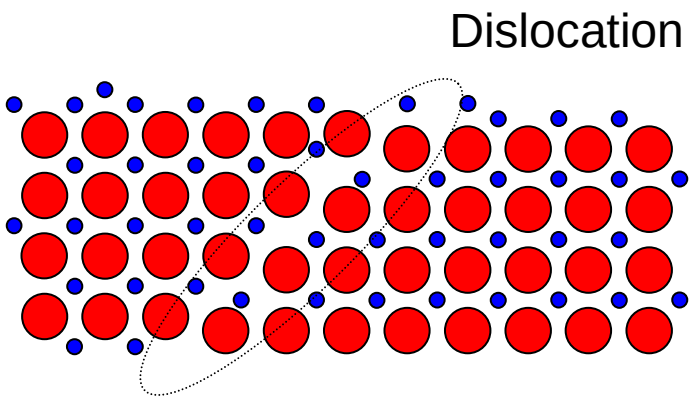
1)They can be both objects of the volume and surface of the material simultaneously (dislocation lines and their outcrops);
2) They are elementary carriers of high deformation energy;
3) They concentrate point defects around themselves, forming clouds of defects;
4) They can be sources of crack generation and versa products of crack development;
5) They are centers of electron emission during moving, mutual annihilation or exit to the surface under the influence of mechanical loads;
6) They have the ability to multiplication under the influence of mechanical loads through a number of known mechanisms

All these features are suitable for the vacuum breakdown initiation factor.

Discussion

Energy of dislocation per atom-atom distance

$$w = a\frac{Gb^2}{4\pi(1-\mu)}\ln\frac{R}{r}$$



G = 43·10^9 Pa - shear modulus;
a =3.6·10^{-10} m - inter-atomic distance
μ = 0.38 - Poisson ratio;
b= 2$^{-1/2}a$ - Burgers vector length;
r - radius of the dislocation core;
R - radius of the elastic force zone

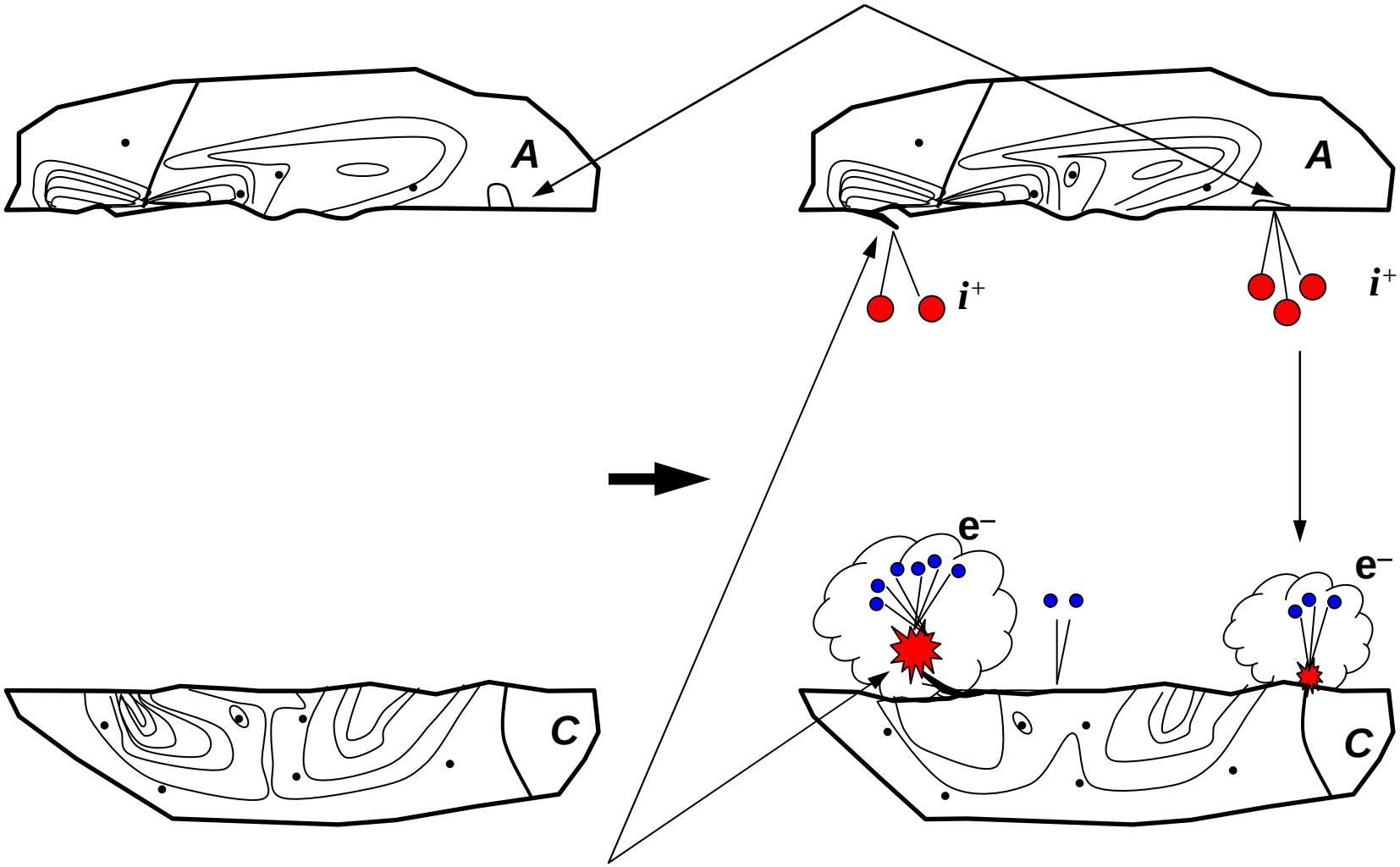
R/r ~ 10^5–10^6 for single crystal

w ~ 10 eV

This value is more than interatomic bond energy and more than electron work function.

Suggested mechanisms of breakdown initiating

Unstable dislocation half-loop as a source of ion emission at anode



Embrittlement and exfoliation of the material

Conclusion

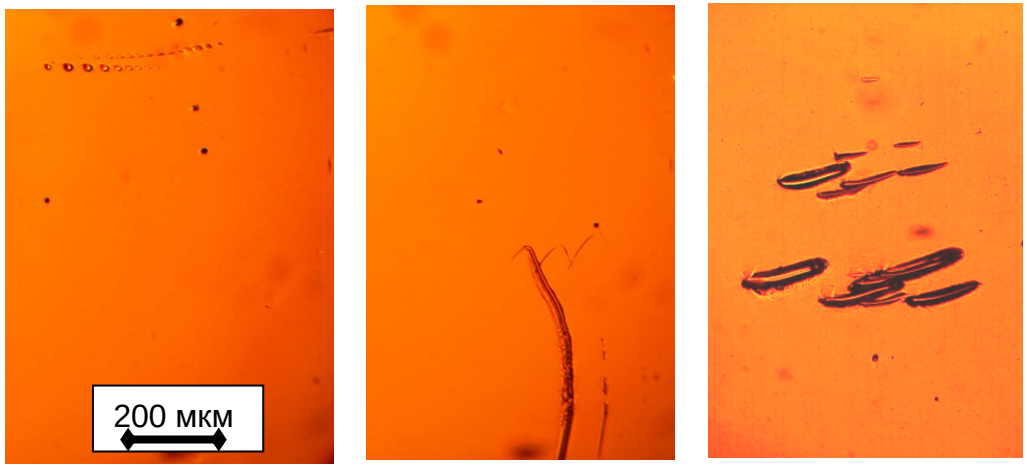
The following experimental facts have been established for the pulse breakdown of VGs with single-crystal copper cathode:

1) There is a preliminary pre-spark stage of vacuum breakdown associated with plastic phenomena in the near-surface layer of the cathode material;

2) The spatial distribution and spreading of the explosion emission centers at the beginning of breakdown development in millimeter VGs appreciably determined by the position of the dislocation outcrops on the cathode surface.

Thank you for your attention!

Appendix



Appendix