In-situ observation of field-induced nano-protrusion growth on a carbon-coated tungsten nanotip

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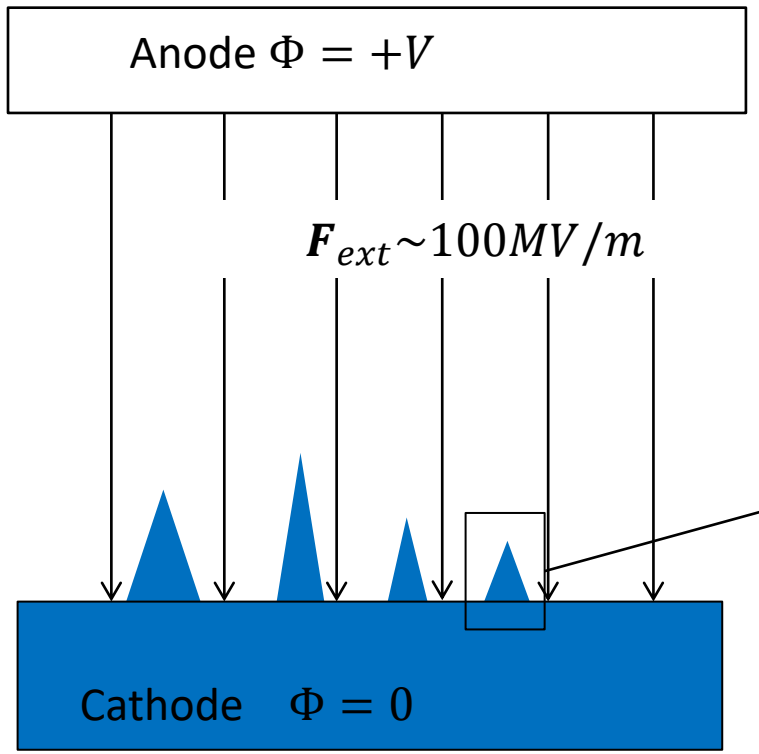
MATTER

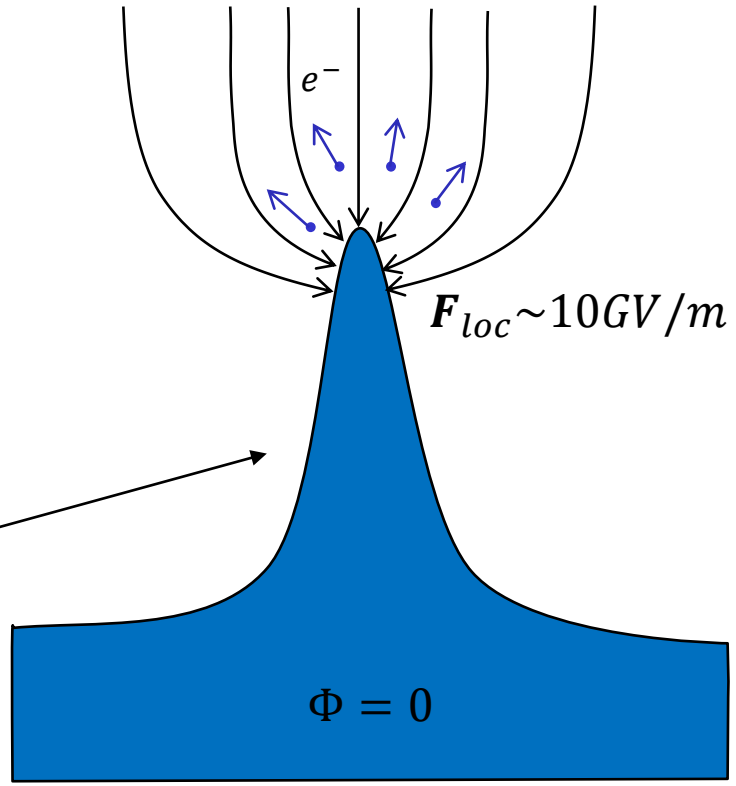
MeVArc 2024, Lake Tahoe, USA

Vacuum breakdown stages

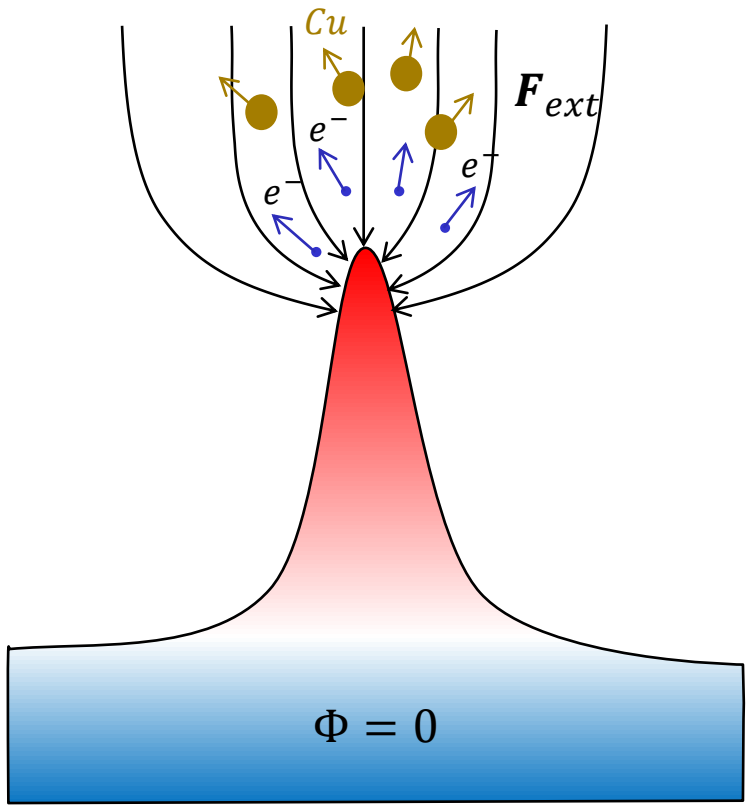
Stage 0: Flat surface



Stage 1: Field emission

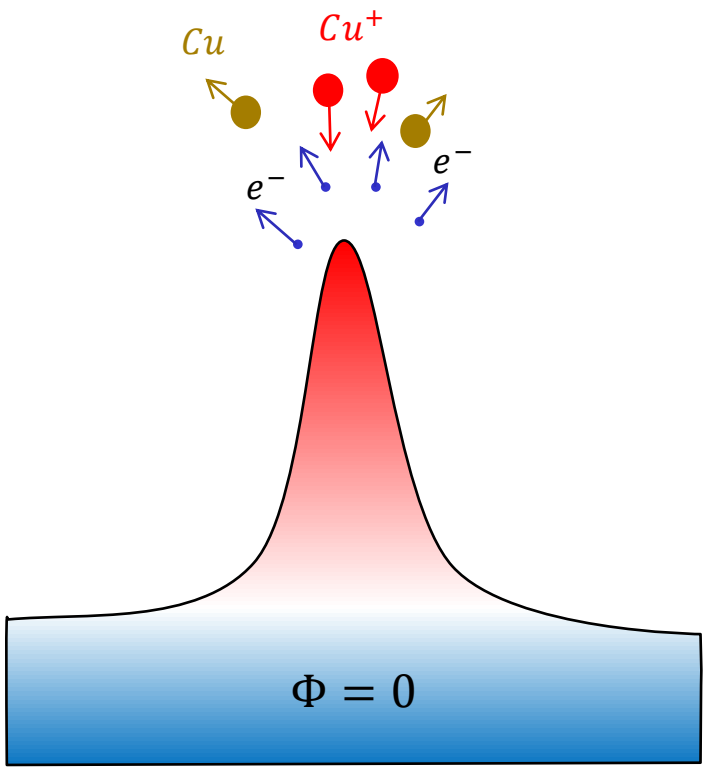


Stage 2: Field emitter Thermal Runaway

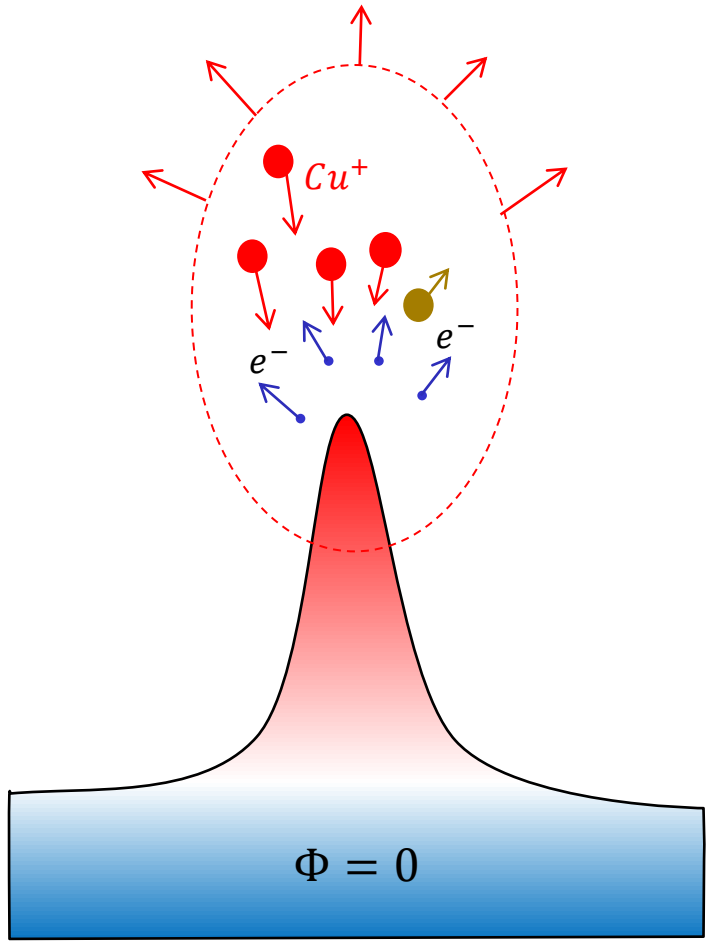


Vacuum breakdown stages

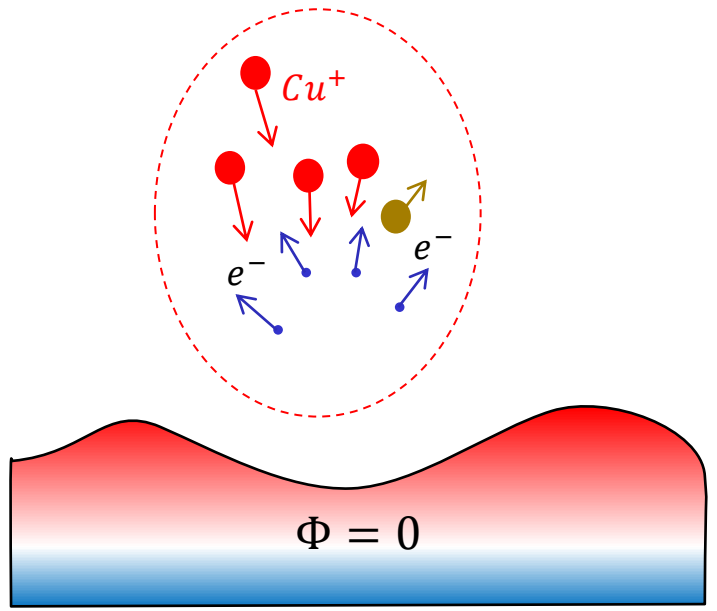
Stage 3: Ionization runaway & Plasma onset



Stage 4: Plasma expansion

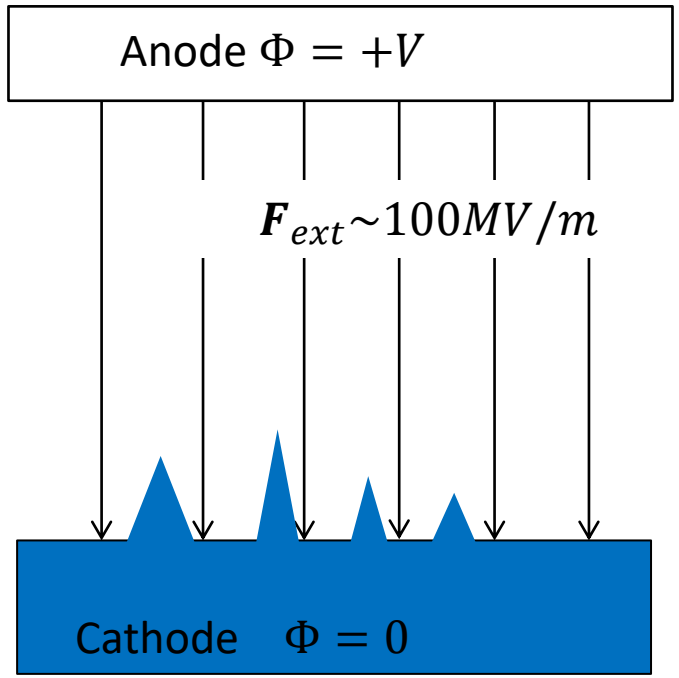


Stage 5: Burning arc, crater formation



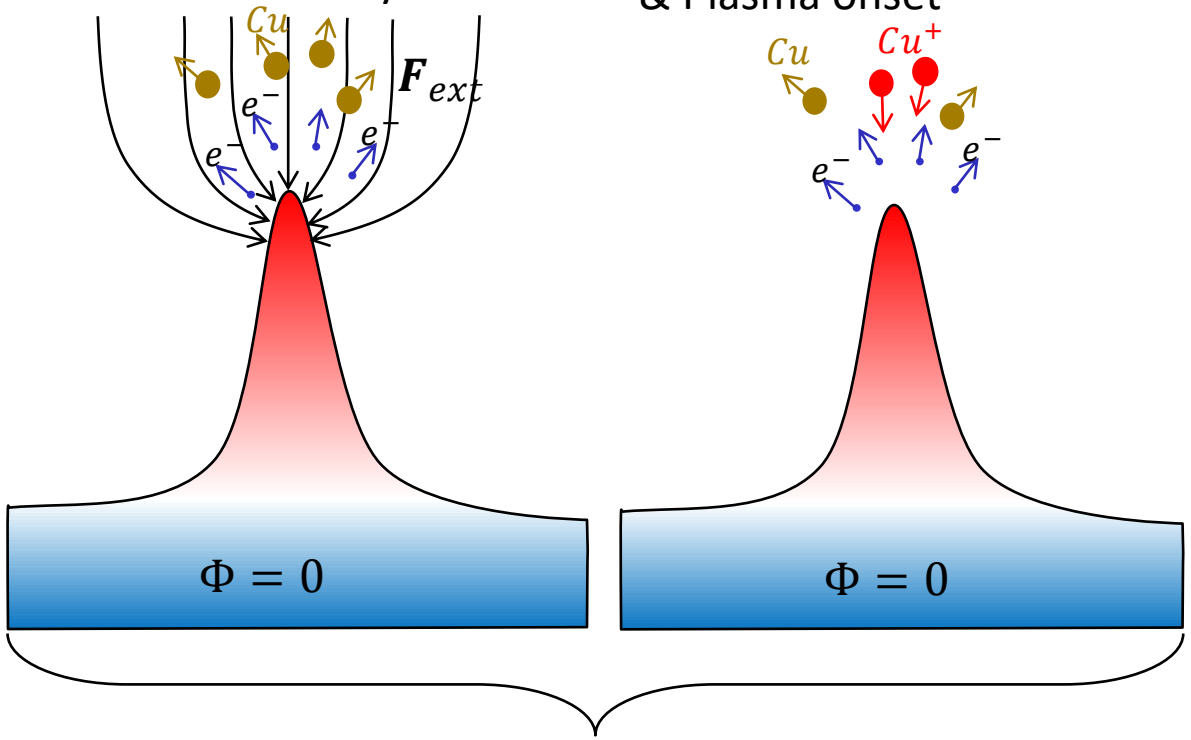
Crucial stages for VBD mitigation

Protrusion formation: Mitigate by material choice, conditioning, vacuum quality, etc



Stage 2: Field emitter Thermal Runaway

Stage 3: Ionization runaway & Plasma onset



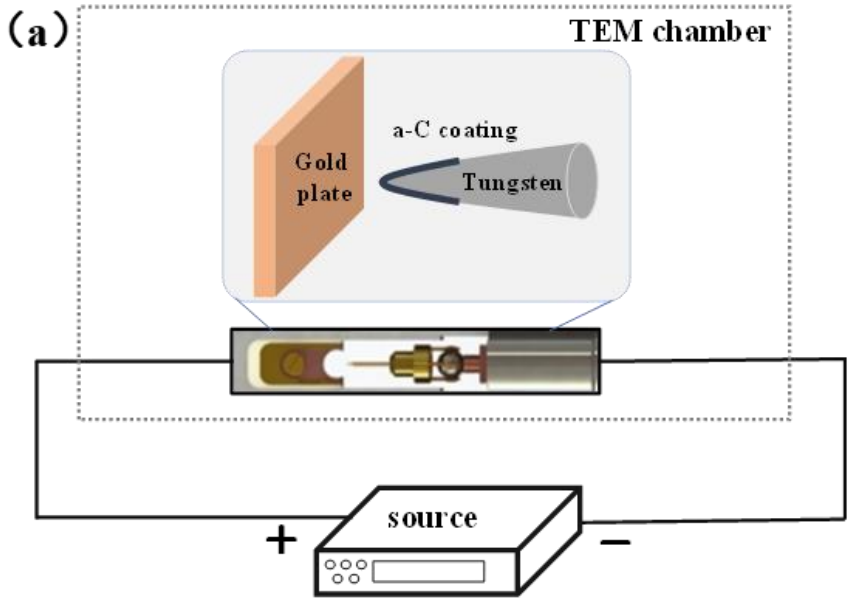
(Not really distinguishable): Mitigate by EM power coupling (RF design of structures)

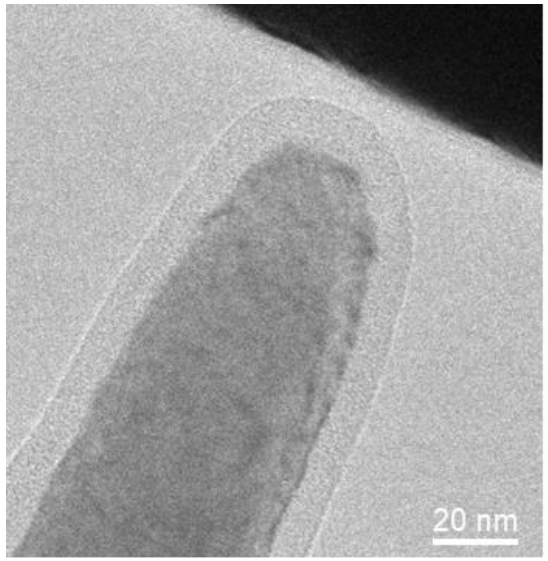
Stage 1: tip growth?

Ideas on the table:

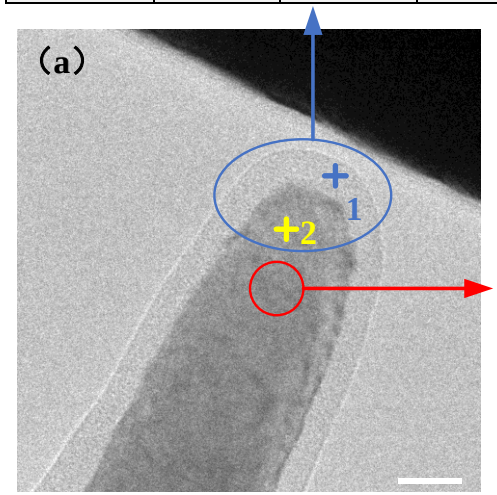
- surface diffusion under field (native metal)
- surface diffusion under field (contaminants – C)
- Field-induced deposition of contaminants (mainly C)
- Dislocation activity causing plastic deformation driven outgrowths
- Field-induced plastic deformation of contaminant layer
- Macroparticles (AKA “Cranberg scenario”)
- Tips are already there (natural roughness) and we can’t get rid of them
- … more …. (?)

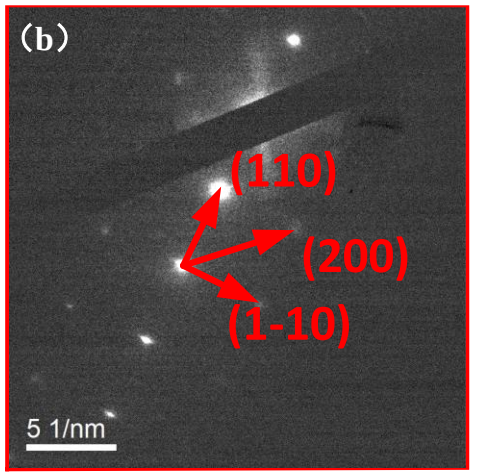
Experimental setup

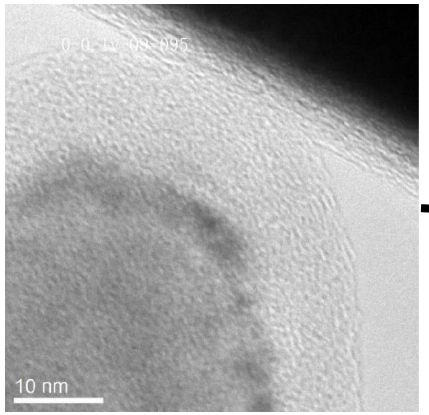


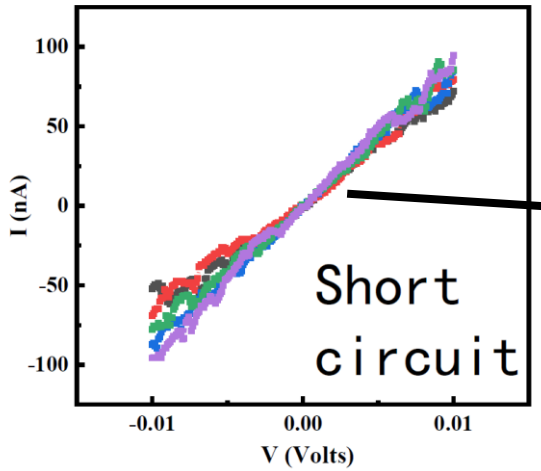


(c)	C element		O element		W element	
	Wt%	At%	Wt%	At%	Wt%	At%
Point 1	98.19	99.04	1.22	0.93	0.59	0.04
Point 2	39.95	89.69	3.23	5.26	56.82	8.06







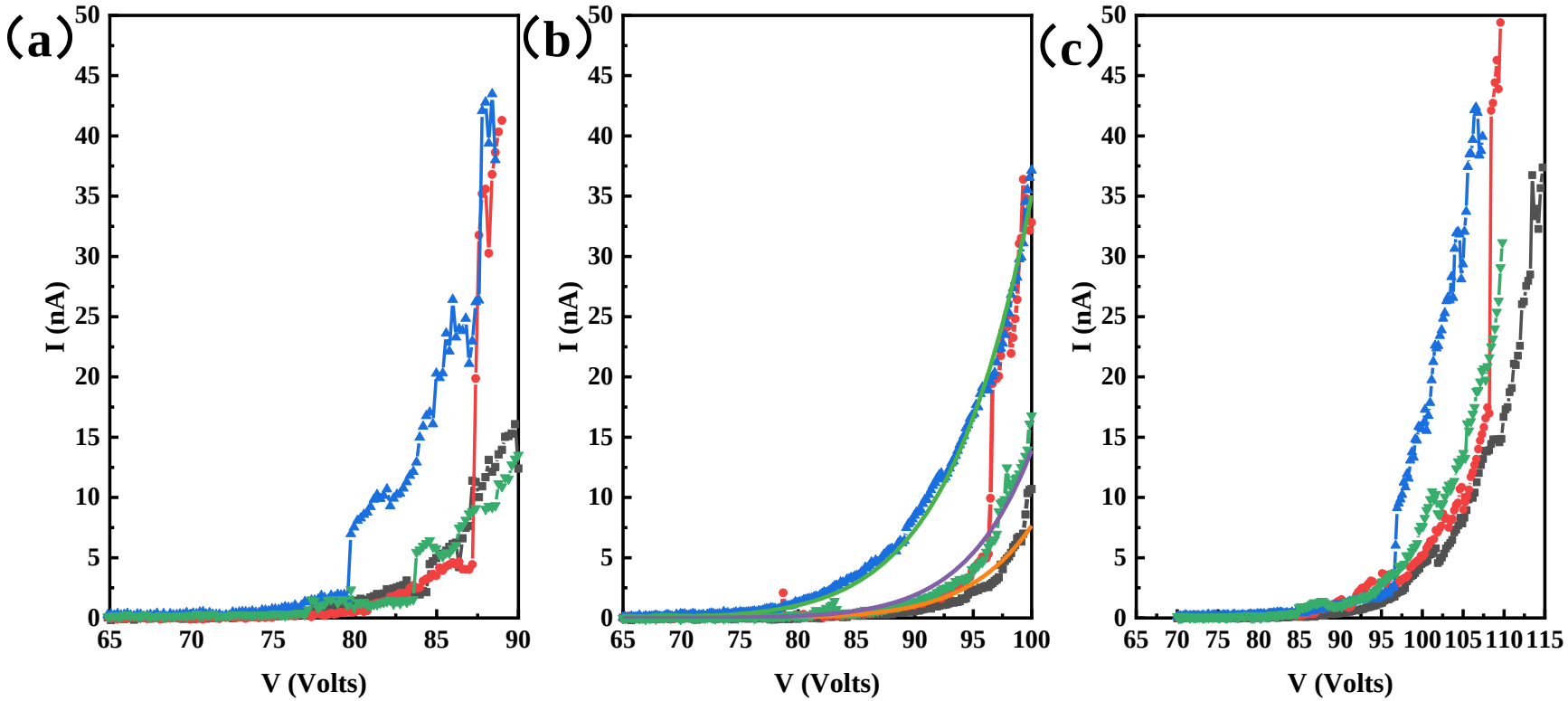


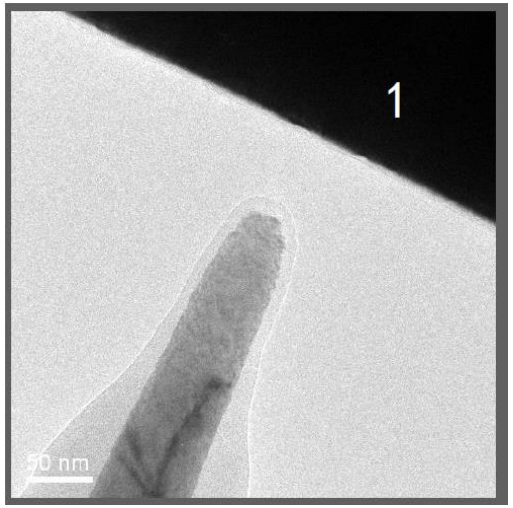
$\rho \approx 3.3 \times 10^{-3}\ \Omega\, m$

Consistent with:

- Amorphous C with high graphitic component

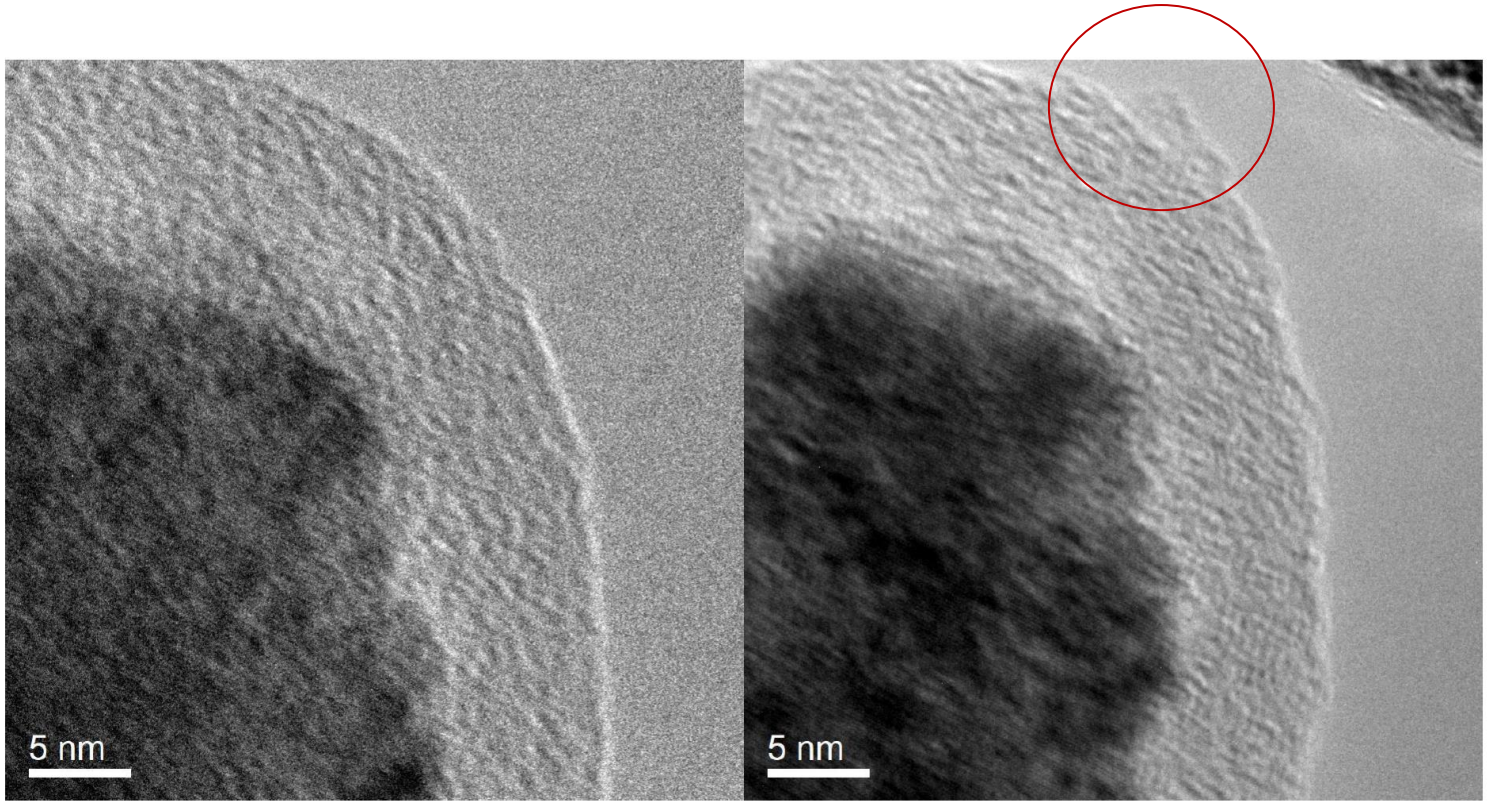
“jumpy” I-V Field emission curves





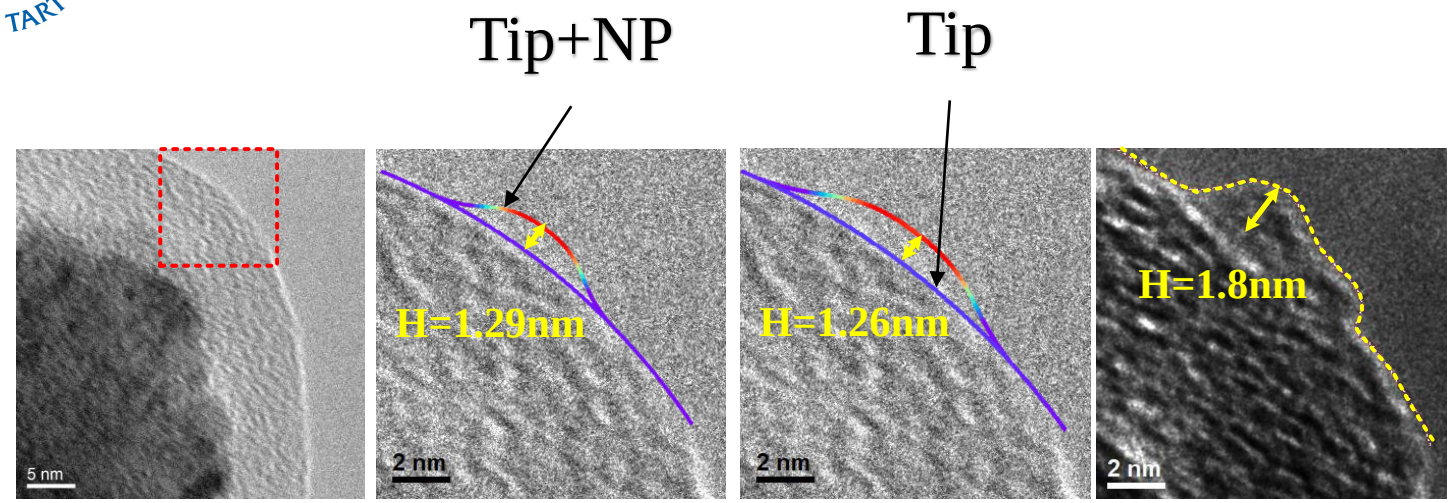
Why does I-V jump?

- Hypothesis: field-induced a-C nanoprotrusion growth

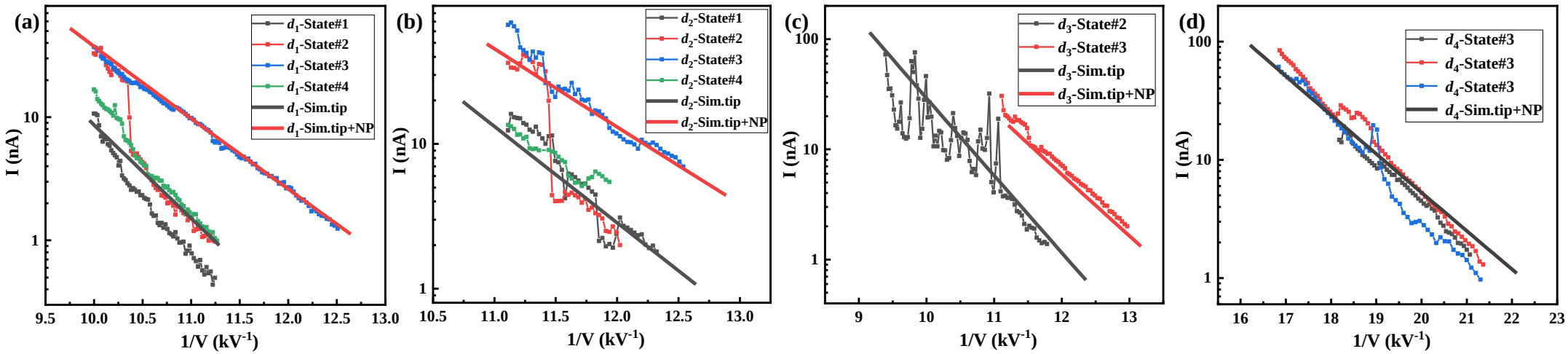


- Same mechanism causing VBD??

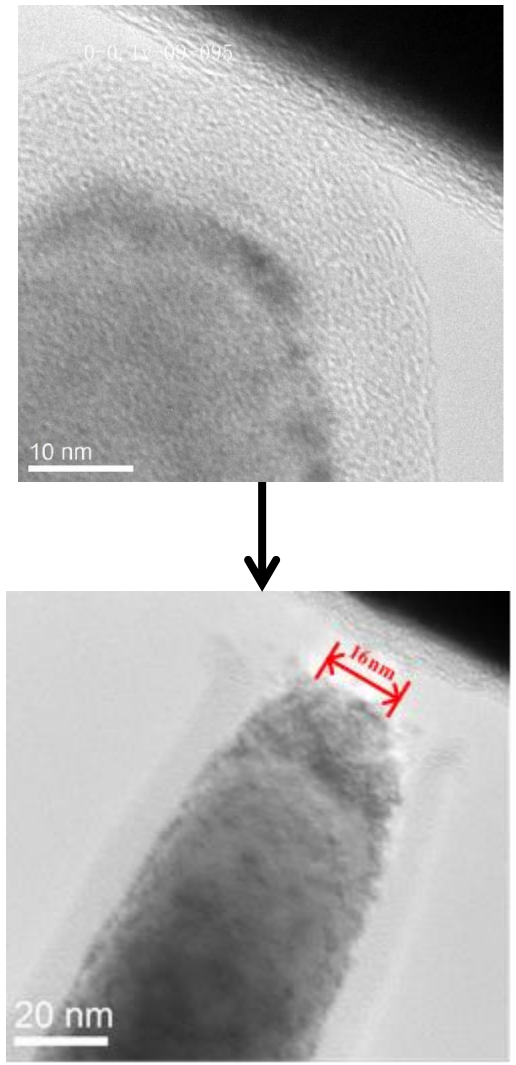
Simulation of I-V curves

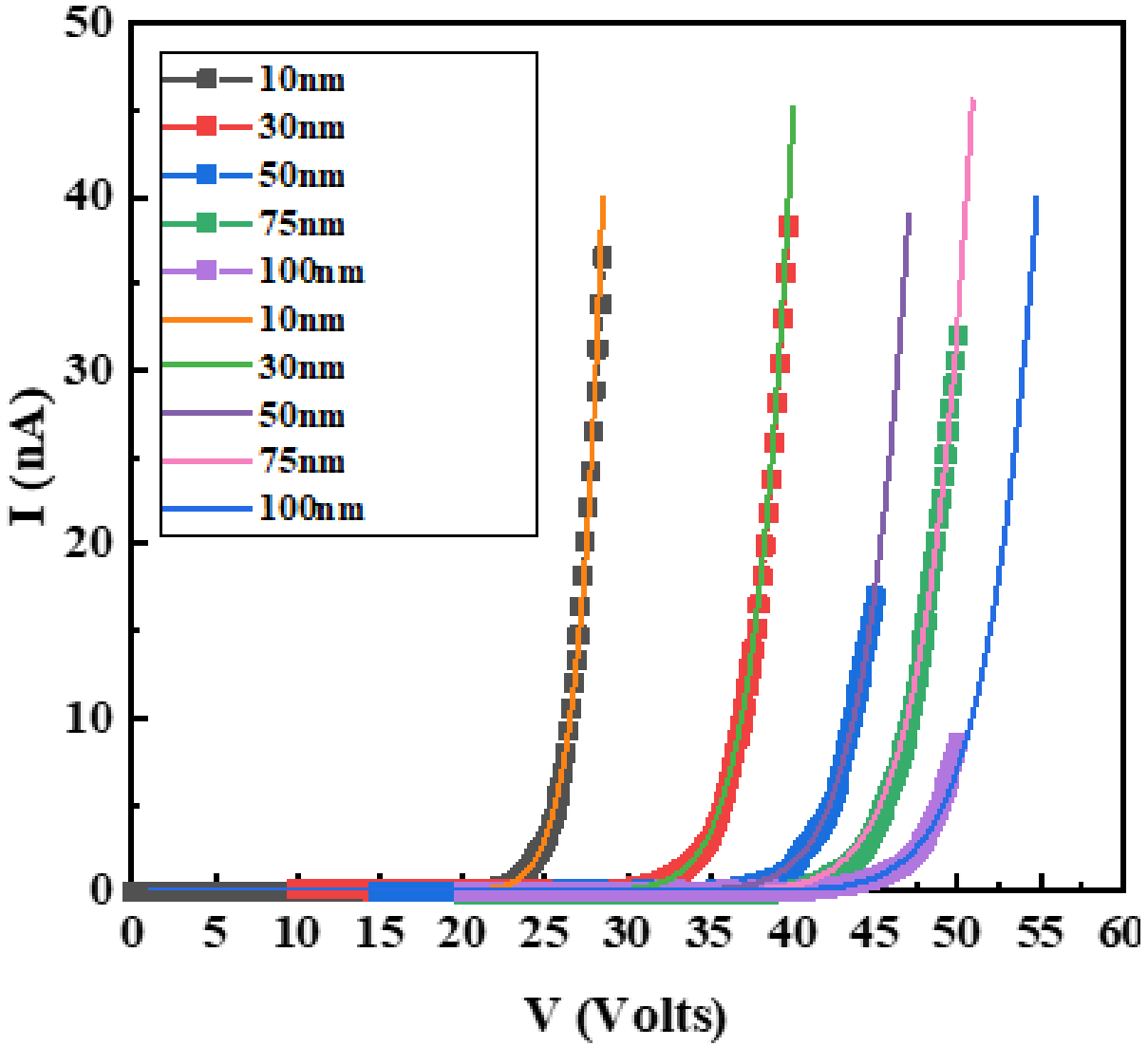


Gap distance (nm)	β_{tip}	β_{NP}	A_{tip} (nm^2)	A_{NP} (nm^2)
d_1(50nm)	1.975	2.6	3743	237
d_2(37nm)	1.67	2.1	2980	315
d_3(41.5nm)	1.77	2.26	3305	266
d_4(17nm)		1.58		159

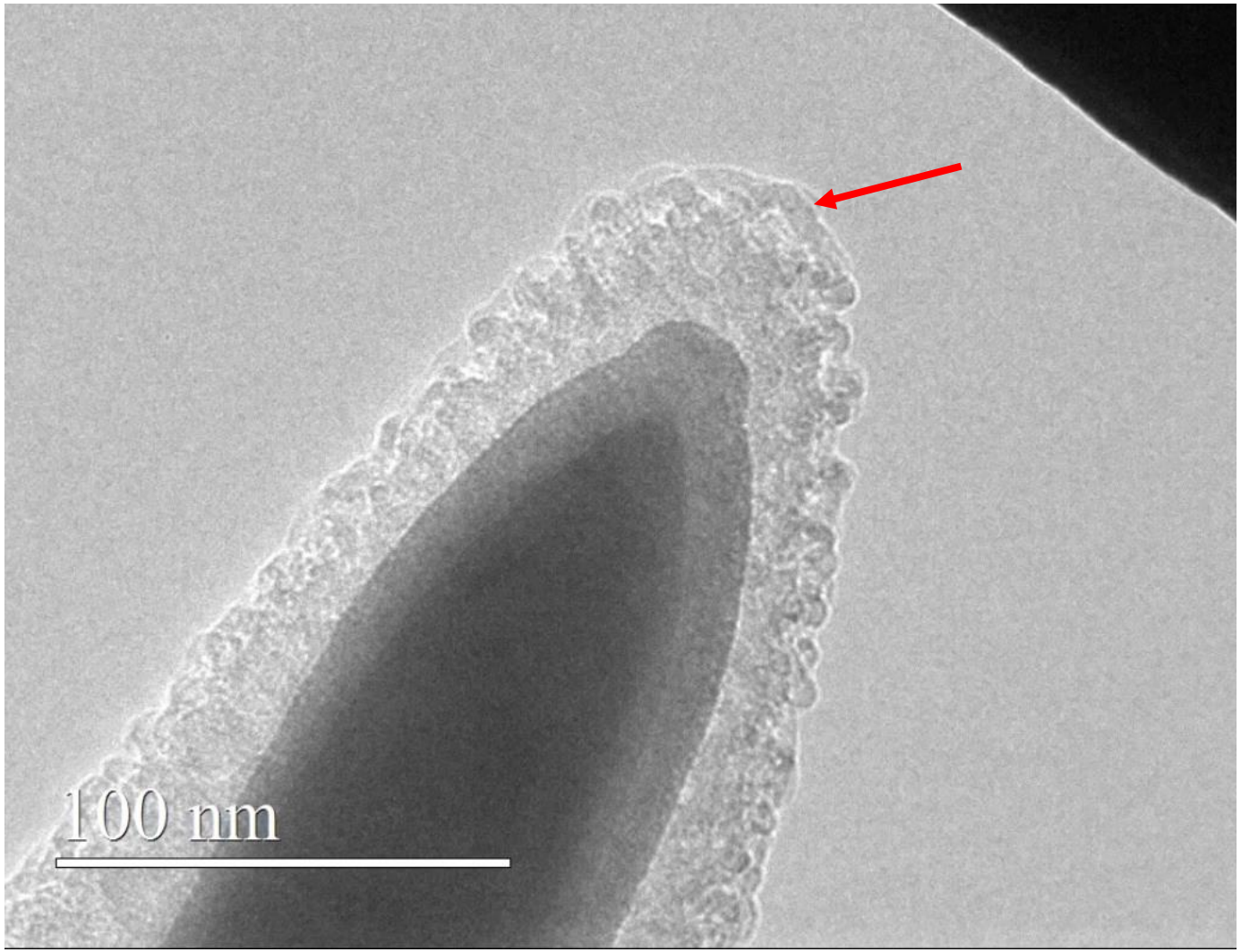


Burning the C out





Observing NP growth real-time



Considering plastic deformation

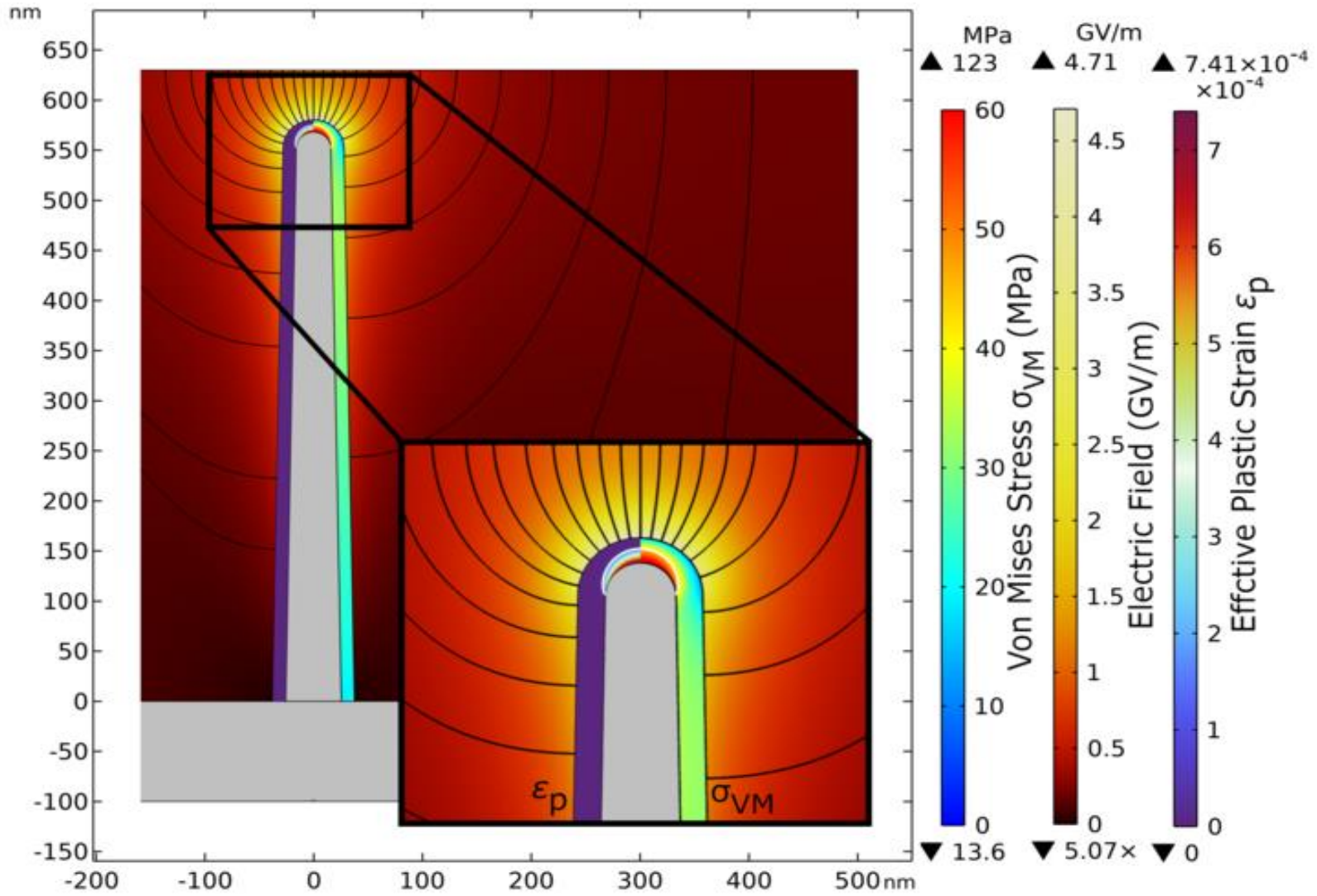
- Elastoplastic FEM model
- Properties fitted to nano-indendation results of a-C
- Plastic deformations not observed at relevant fields

➢ Plastic deformation cannot explain the observed growth

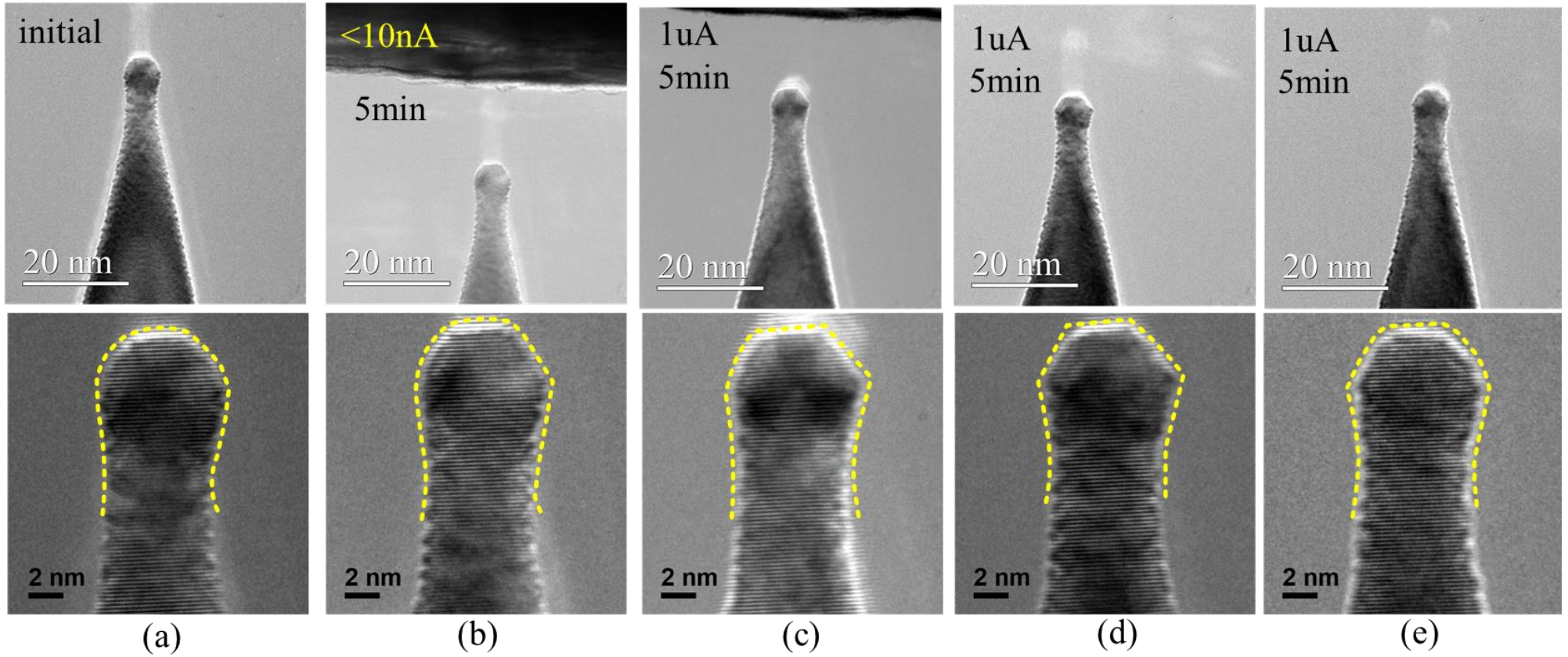
➢ Remaining possible hypotheses:"

- ❑ Field-induced diffusion
- ❑ Field-induced deposition

❑ We cannot tell yet which one is responsible

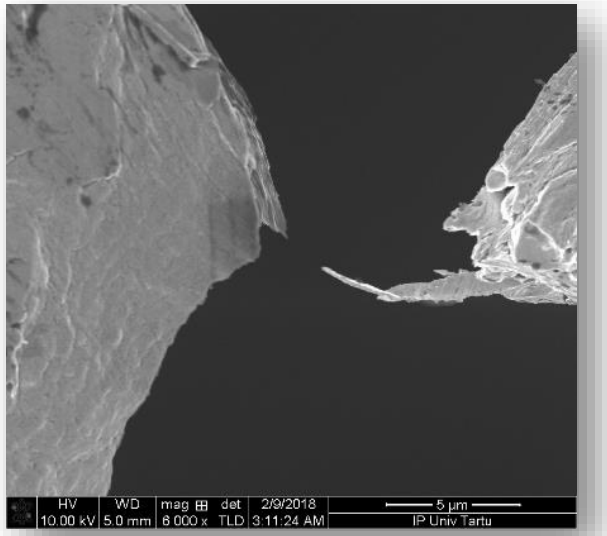


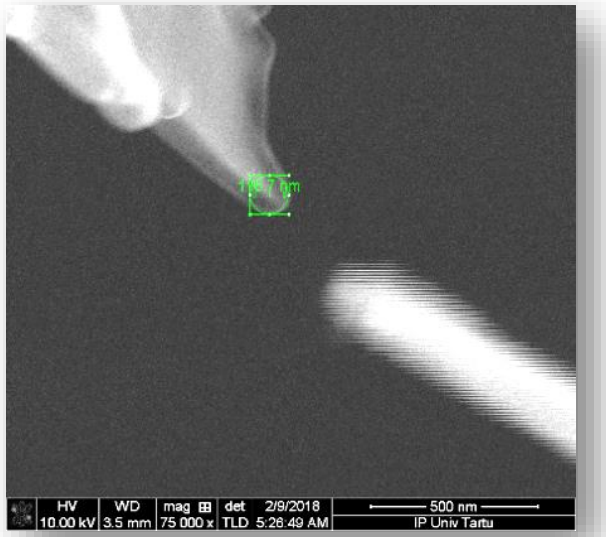
Considering deposition

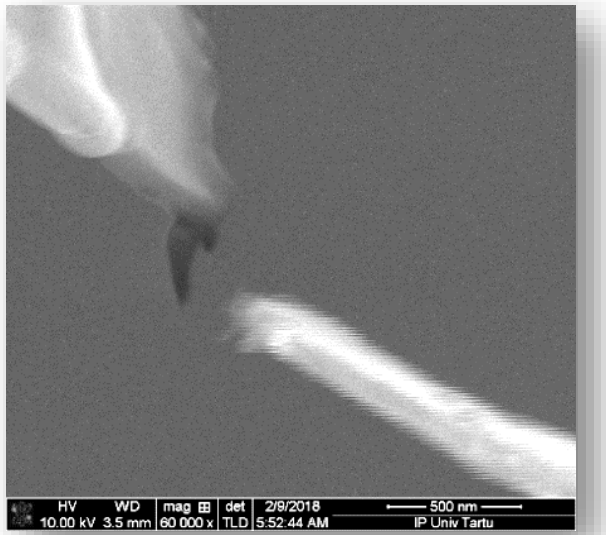


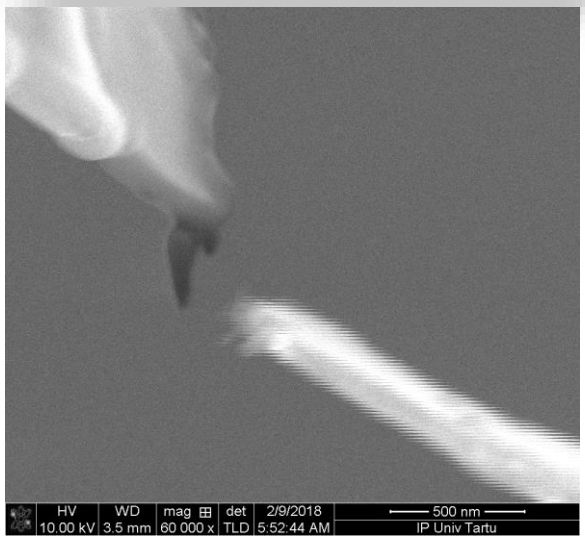
- In a clean W tip emitting under the same conditions, no growth was observed
- The emission and field are enough to change the shape of the W tip (faceting), but no deposition

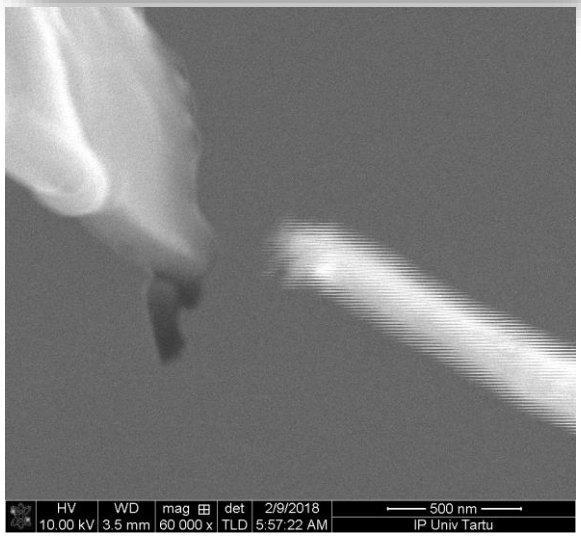
Old experiments at UT

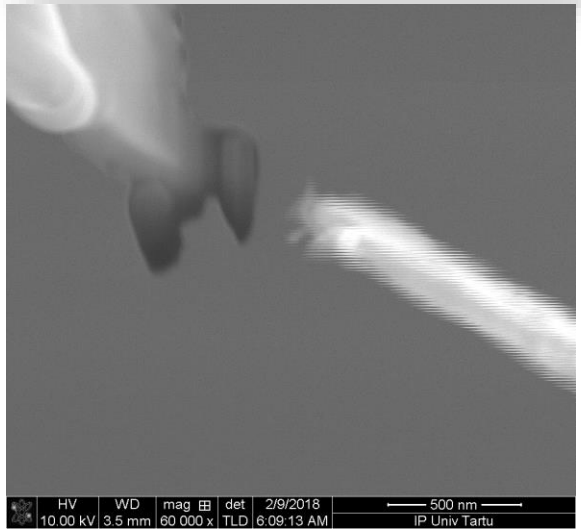












Conclusions

- Nano-protrusion (NP) growth on the a-C coating layer of a W nanotip during field emission
- We attribute it to field-induced biased surface diffusion of the a-C surface atoms, after excluding field-induced plastic deformation and deposition.
- This offers a plausible mechanism of the appearance of field enhancing features necessary to initiate electrical breakdown in vacuum.