The Harvey M. Krueger Family Center
for Nanoscience and Nanotechnology

האוניברסיטה העברית בירושלים
THE HEBREW UNIVERSITY OF JERUSALEM

Model and observations linking plastic activity to arc nucleation

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PAZY
EXCELLING IN SCIENCE

Breakdowns in High gradient systems

- Brakedowns are: Rare events.
  Plasma is formed in a region where high gradient is maintaned in a vacuum.
  There is no single identifiable mechanism leading to the nucleation of breakdown.
- Breakdown rates depend on “conditioning” :
  High gradient pulse length and gradient are increased with time to allow system to reach full spec.
  There are clearly various causes for BD: extrinsic (contaminates? Local structural nucleation sites?) that highly depend on system production and conditions. and intrinsic – saturation values are reproducible.

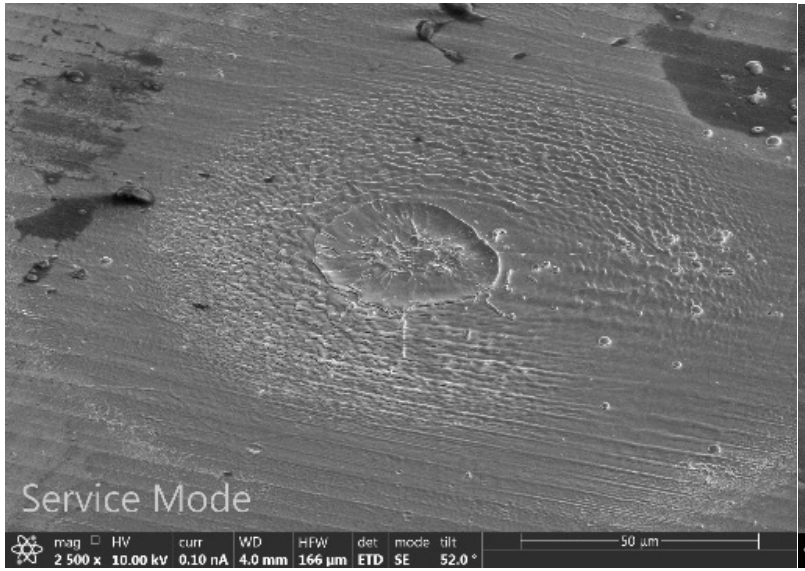
Microscopy of BD events (RF and DC samples)

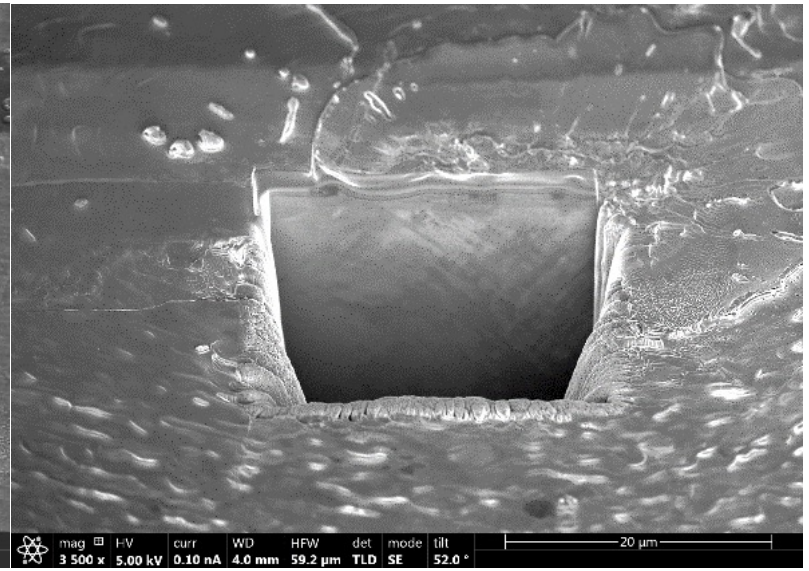
BD are a result of copper plasma formation which creates significant plastic activity at BD site

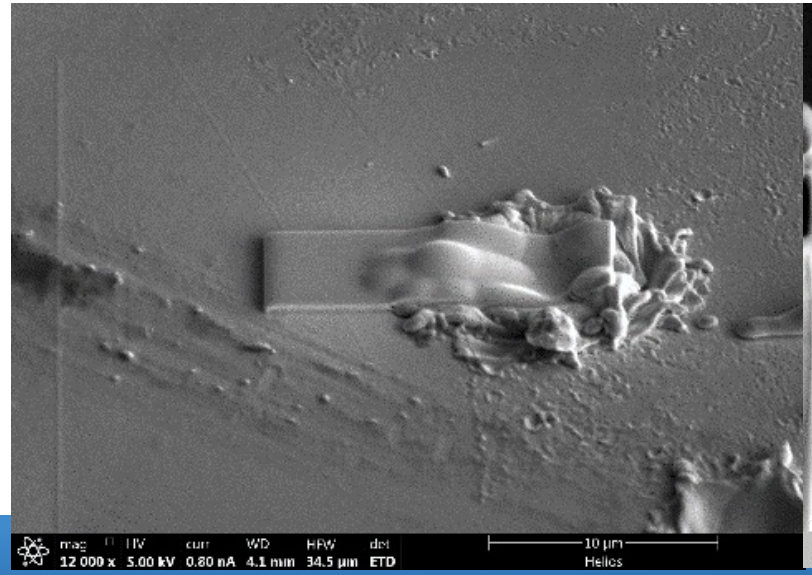
BD craters can be small or engulfed in large pools of melted copper

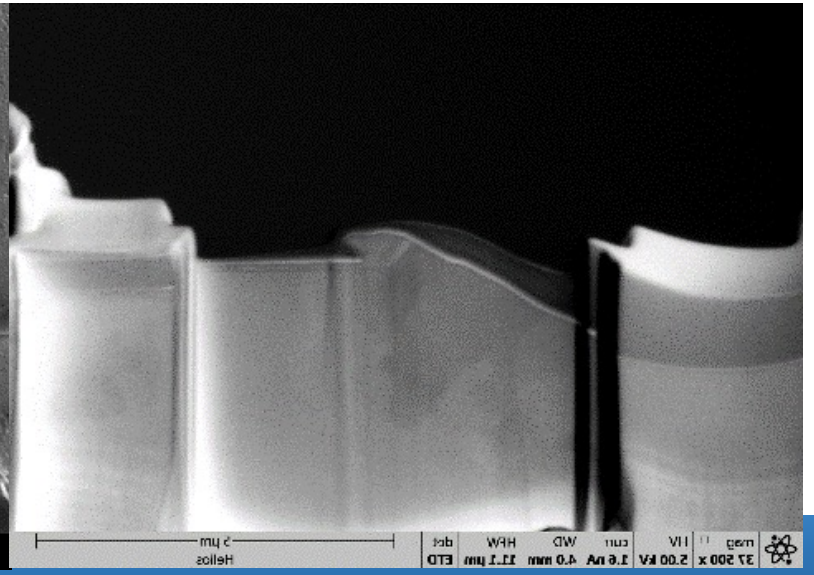
But in general the remnants of these violent events do not explicitly tell us what preceded them…

However – we do see that events are NOT correlated with GB or other large scale features.





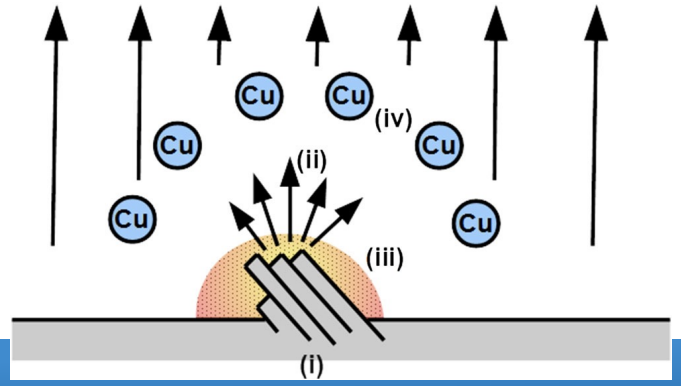


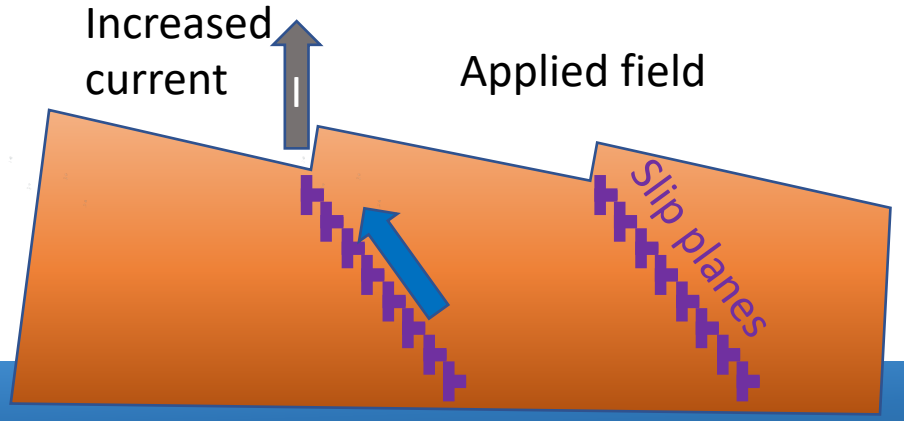


Modelling Breakdowns as rare critical events

High field → critical transition → nucleation → localized emission → Cu plasma → BD

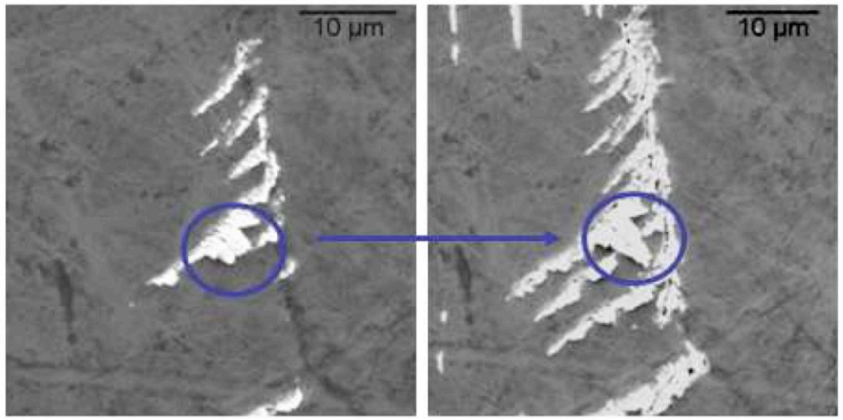
- Underlying assumptions ("knowns"):
  - BD are formed due to rare localized amplification of thermionic emission which leads to emission of neutrals and seeds plasma formation
  - BD involves plasma evolution and surface sputtering.
- Our main hypothesis:
  - Intrinsic breakdowns are initiated due to a critical plastic process.
  - These are driven by collective dislocation motion below the surface which leads to subsequent surface modifications.



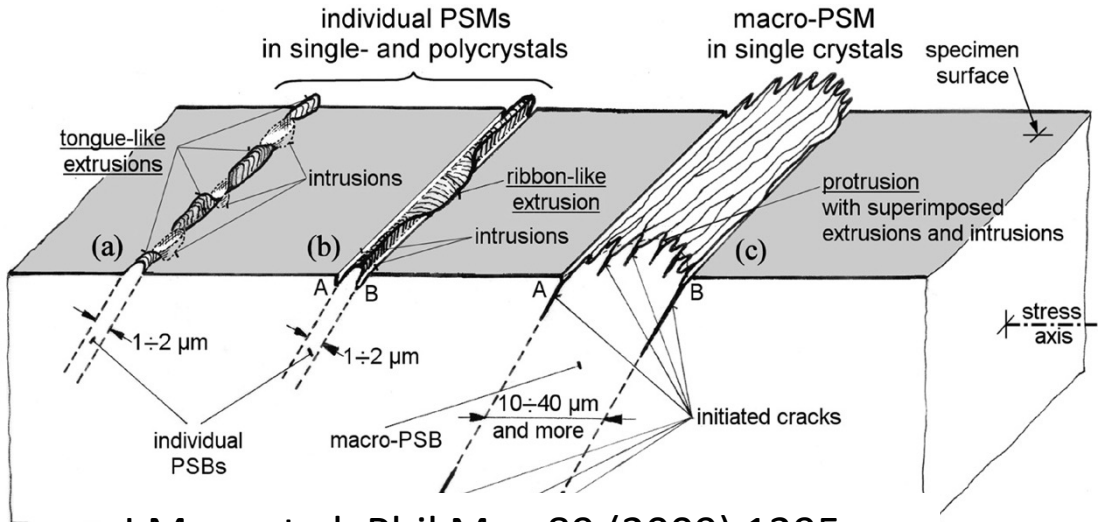


Dislocations are known to create persistent slip bands and protrusions

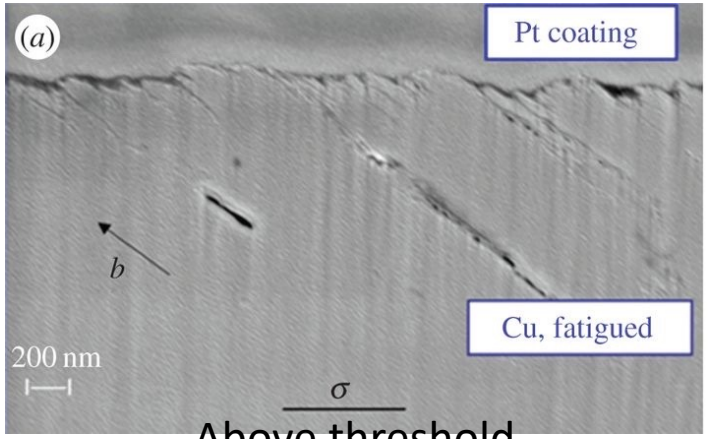
- Previously observed on fatigued surfaces.
- Significant sub-surface PSB leading to surface features.
- Stochastic response at sub-yield stresses.
- PSB exist in various scales – down to 10 nm. These can lead to sudden increase in current



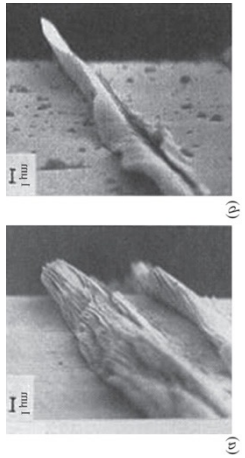
Laurent et.al. Phys Rev STAB 14 (2011) 41001



J.Man et al, Phil Mag 89 (2009) 1295



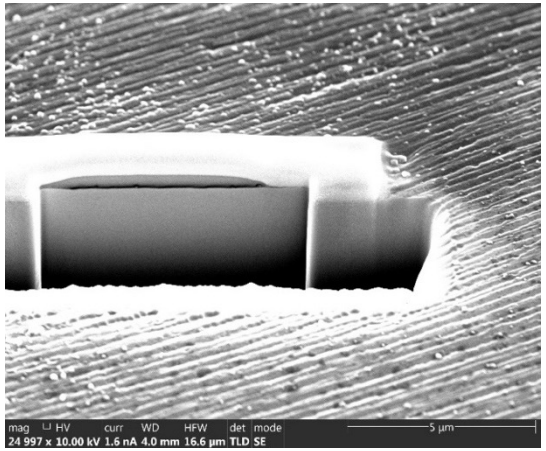
Above threshold

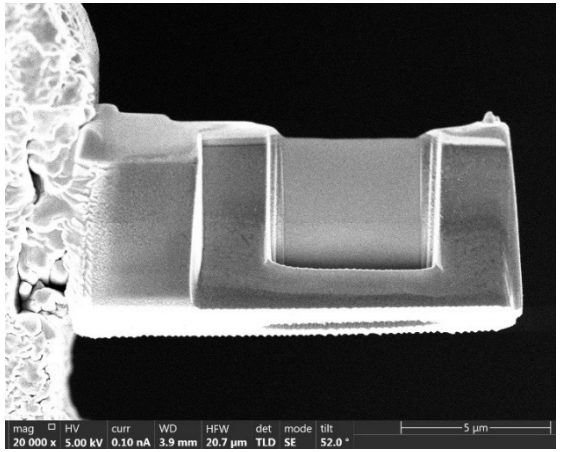


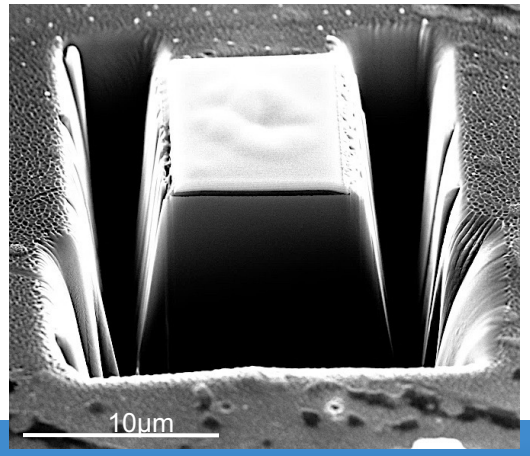
Polycrystal Cu - fatigued ~10^{10} times sub PSB threshold
Haël Mughrabi Phil. Trans. R. Soc. A 2015

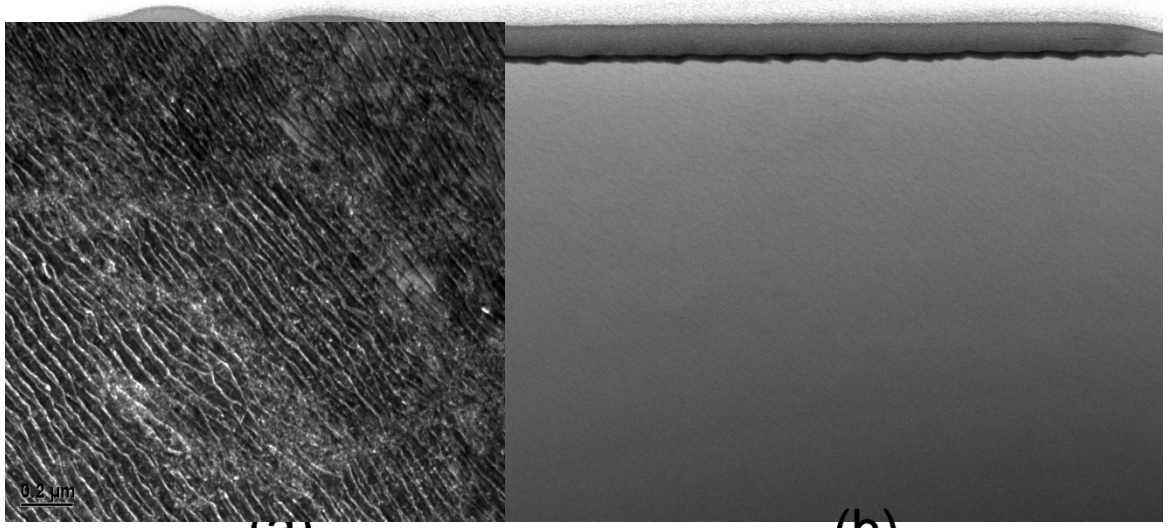
Organized array of dislocations

Cut below surface to estimate dislocations structure using SEM
Using FIB –create top or side view lamellas for TEM and STEM
High density of dislocations is observed

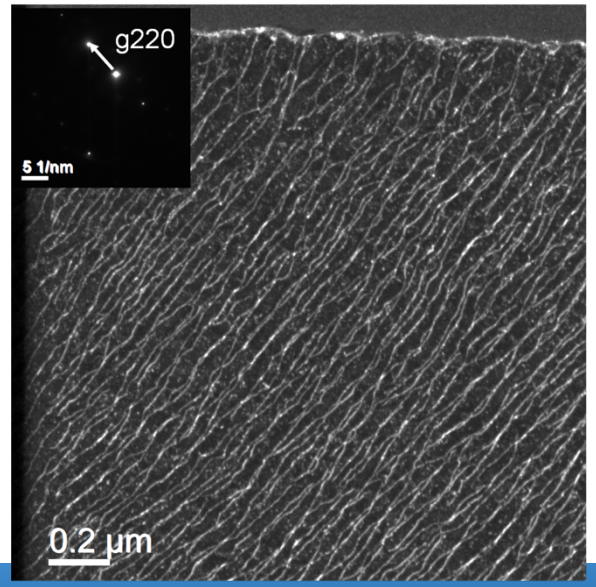


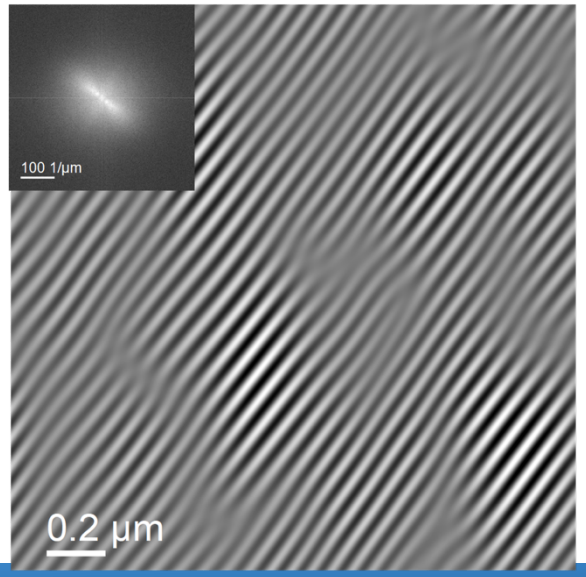






(a) (b)

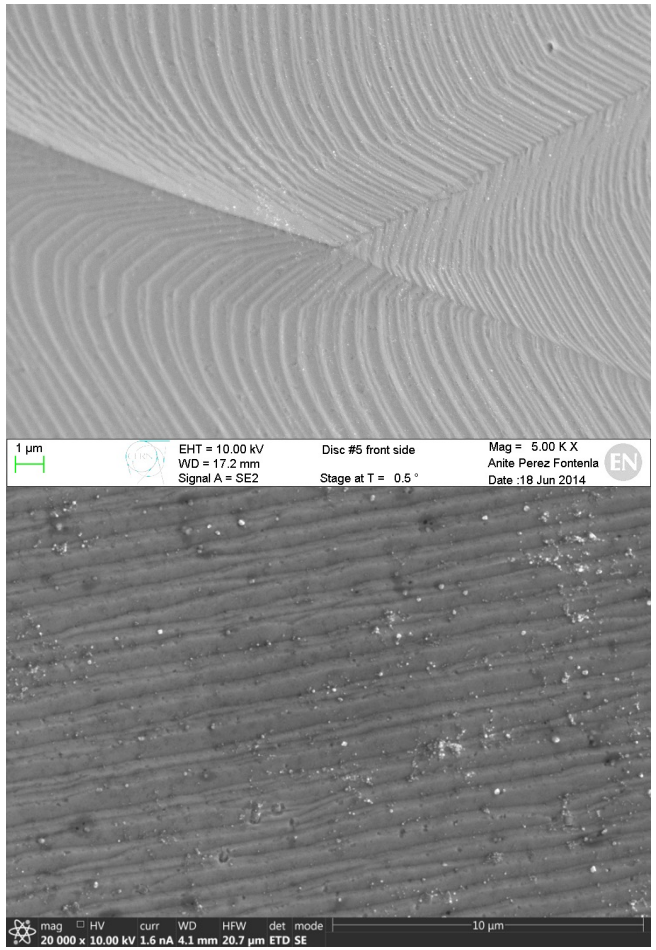




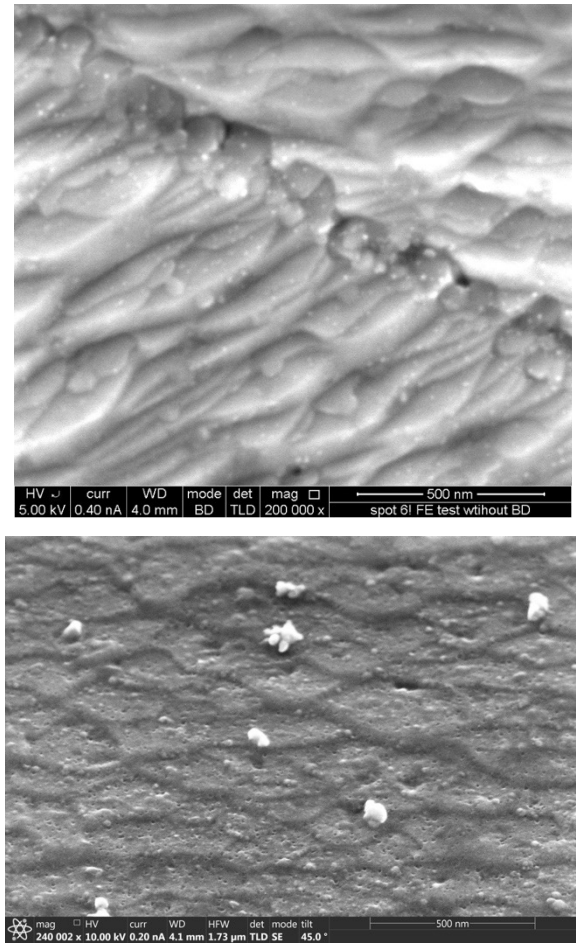
Dislocations below - observable on the surface

- periodic structures, sensitive to grain orientation

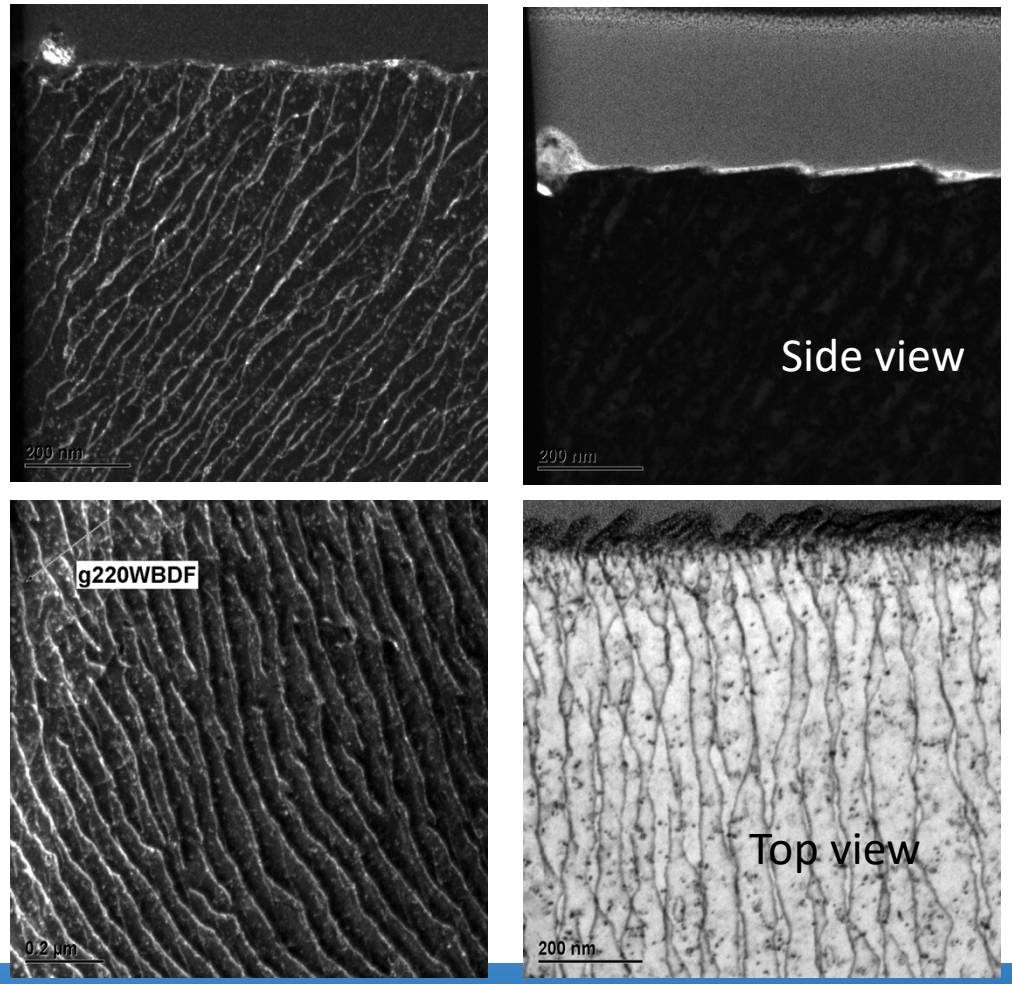
Terraces



Fish Scales



- These are manifestations of dislocation arrays

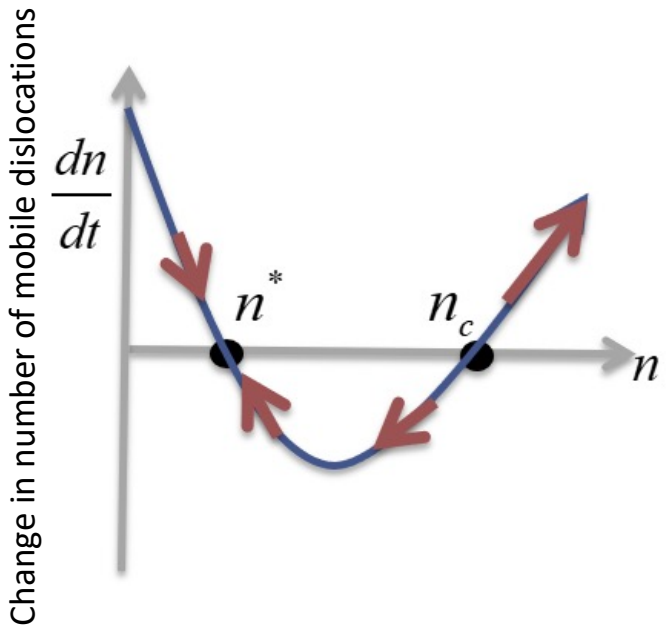


Stochastic model

- Observations: dense ordered sessile array of dissociated dislocations (stabilized by elastic interactions) .
- Under appropriate drive - Such arrangement can become mobile…
  We created a mean field model describing evolution of the mobile dislocation population:

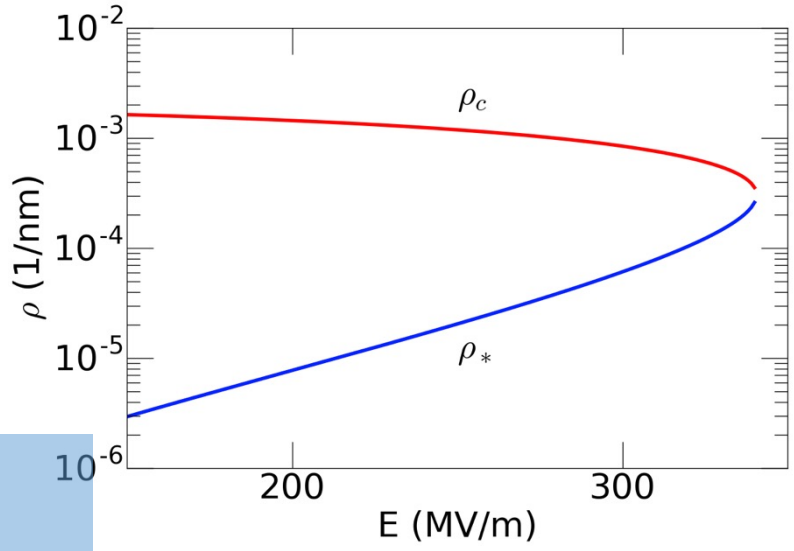
PHYSICAL REVIEW LETTERS **120,** 124801 (2018)

Stochastic Model of Breakdown Nucleation under Intense Electric Fields



Governing equations:

- Increase in mobile population – interactions with field and moving dislocations.
- Arrest due to collisions
- Cooperative critical transition in mobile dislocation population generates nucleation event



We propose that this transition
- start of a runaway in mobile population -
can lead to a nucleation event through its effects on the surface

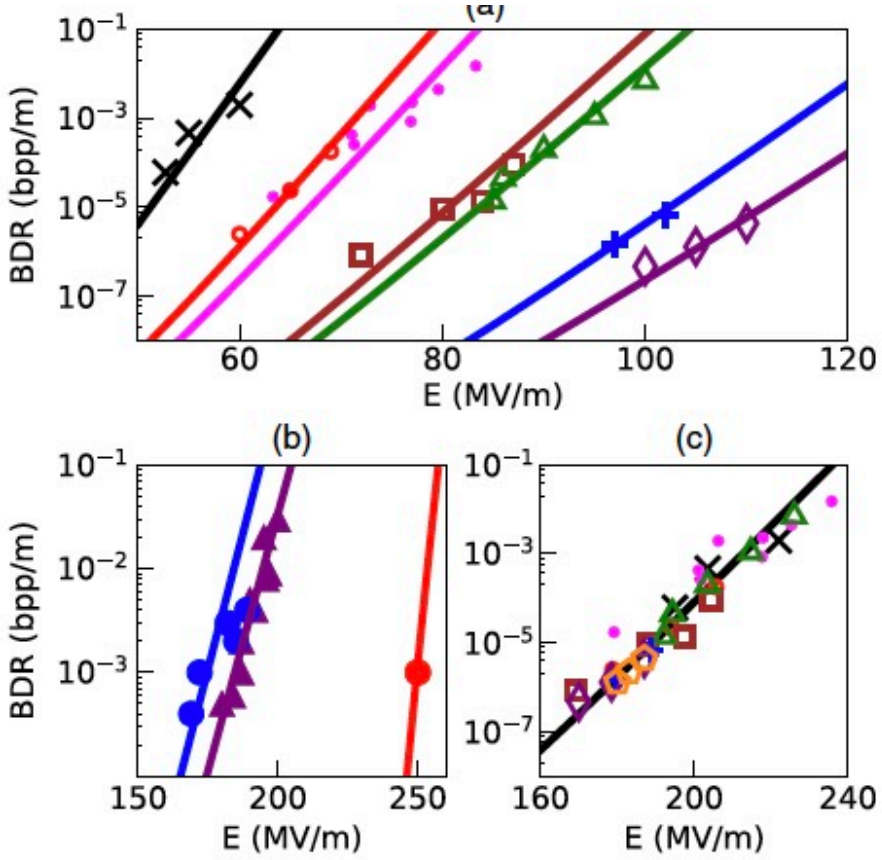
Observations

Consistent fit to breakdown rate dependence on field

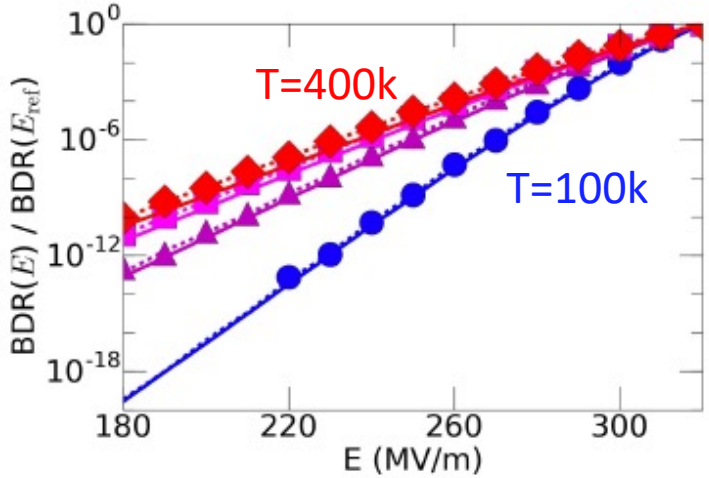
Importance of temperature variation.

- ”Classical” scenario: Temperature effect on BDR versus field curves.
  Dynamic - Ramping up field at various rates. Average “field for BD”

Time dependency - Non-Linear regime.



prior to BD as field is increased fluctuations in the population - and the dark current should be observed!



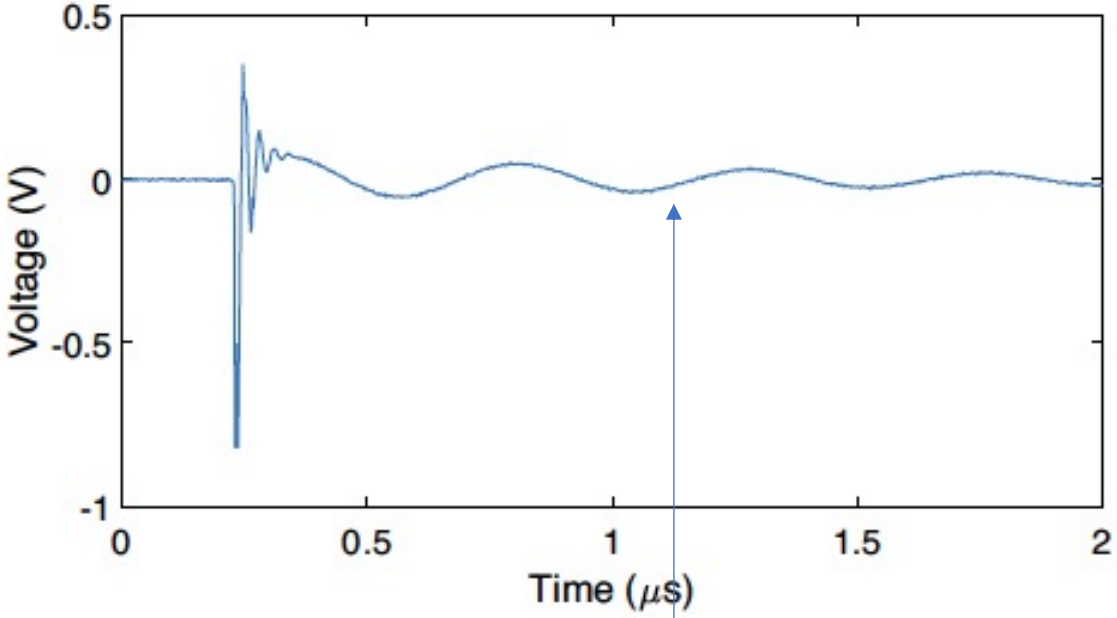
PHYSICAL REVIEW ACCELERATORS AND BEAMS **22,** 083501 (2019)

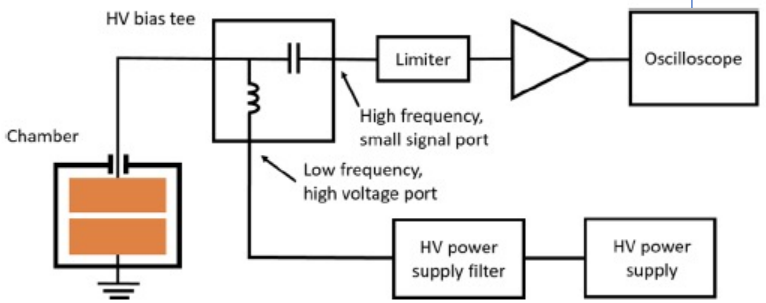
Editors' Suggestion

Theory of electric field breakdown nucleation due to mobile dislocations

Measurments of dark current rare events

(Jan Paszkiewicz, Ruth Peacock)





- These are not BD signals , but are rare distinguishable events.

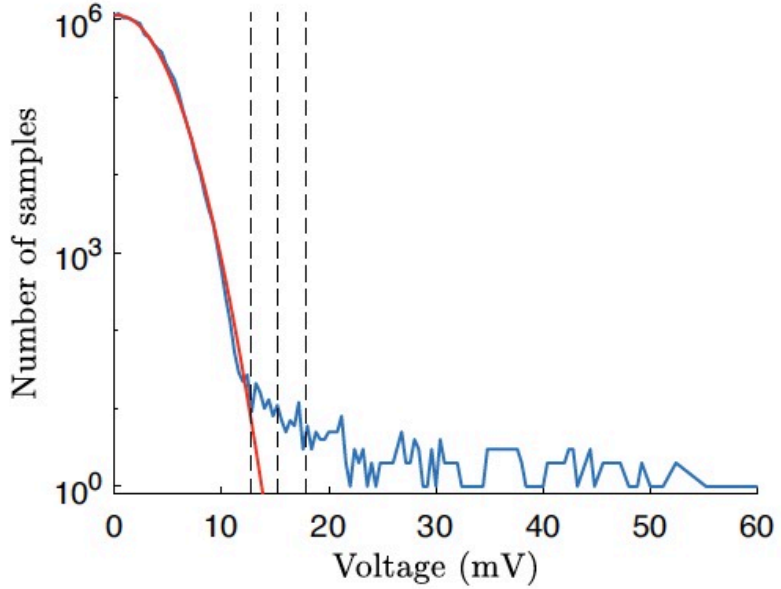


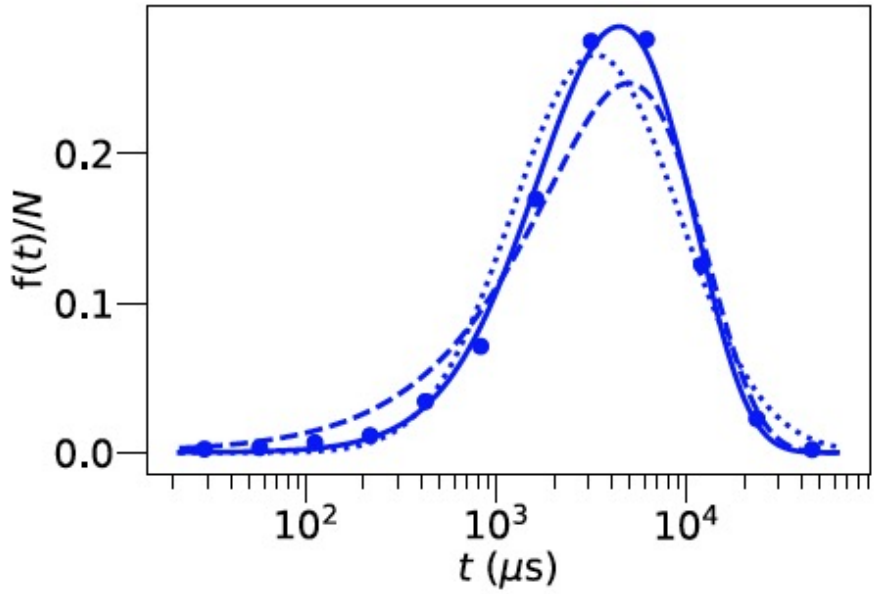
FIG. 9. Frequency histogram of the measured dark current

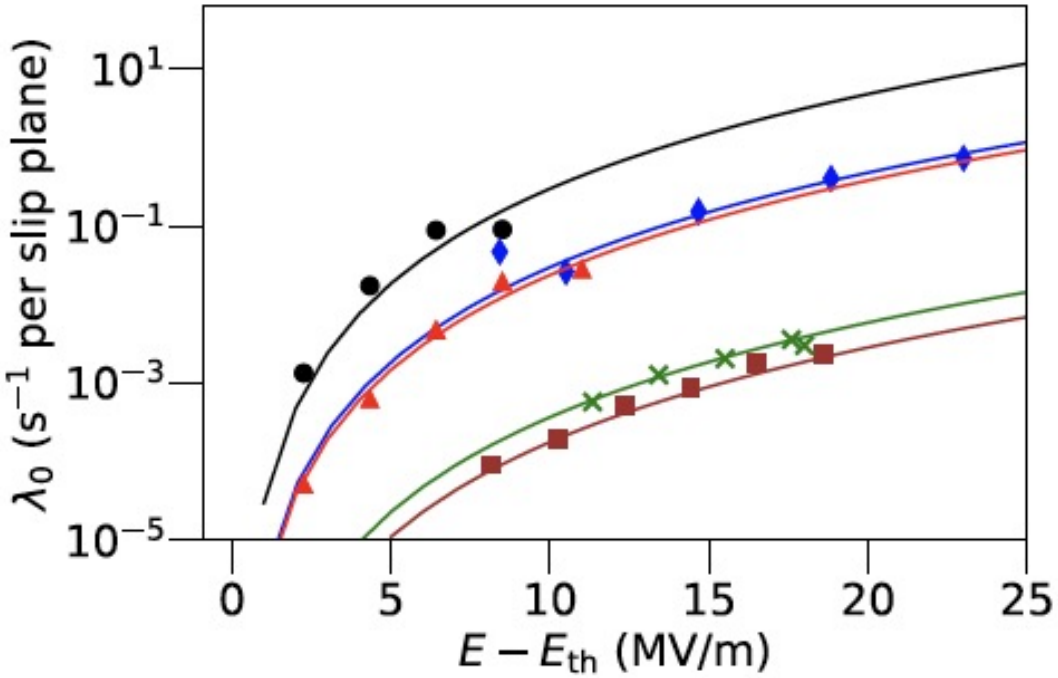
Spikes in dark currents are indeed observed

- Event rate varation with field is reproduced by MDDF based equation.

$$\lambda_0 = \frac{25\kappa C_t c}{G^2 b \Delta\rho}\sigma_0^2 \exp\left(-\frac{E_a - \Omega\sigma_0}{k_B T}\right)$$

- The distribution fits the expected hypoeponential distribution





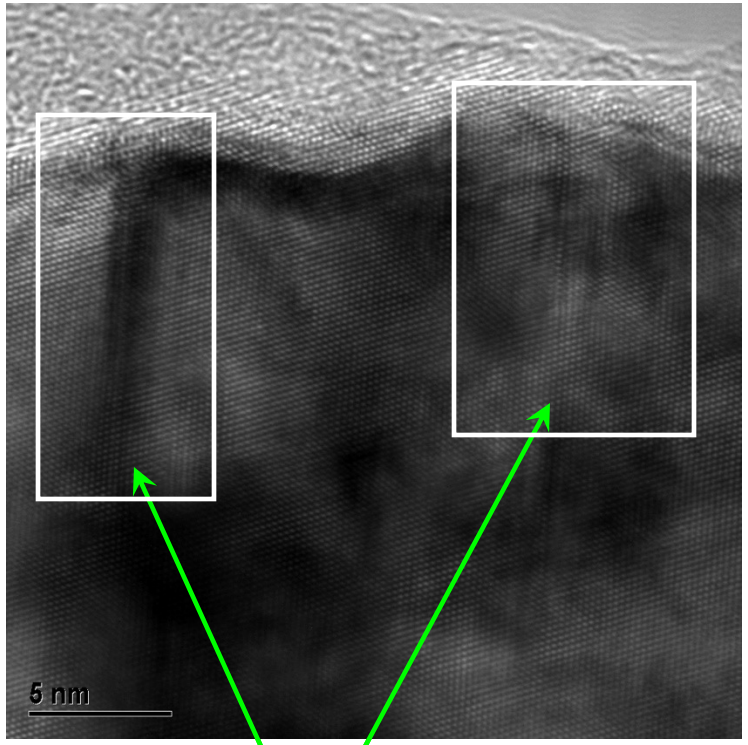
PHYSICAL REVIEW ACCELERATORS AND BEAMS **23,** 123501 (2020)

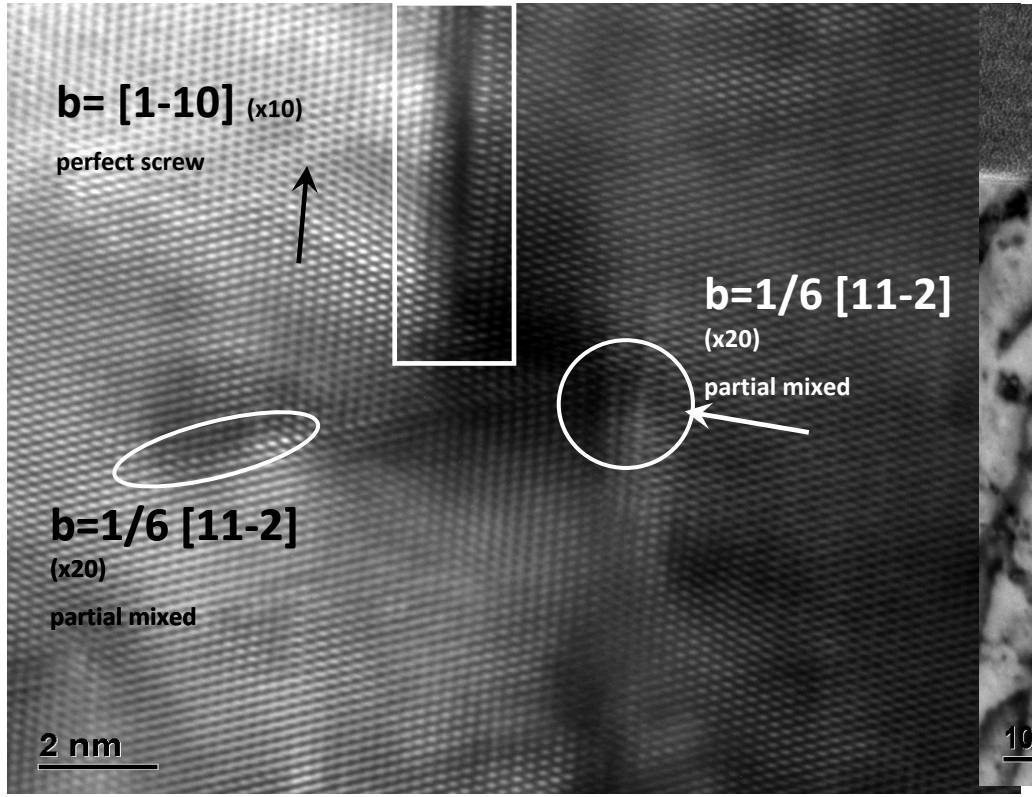
Dark current spikes as an indicator of mobile dislocation dynamics unde intense dc electric fields

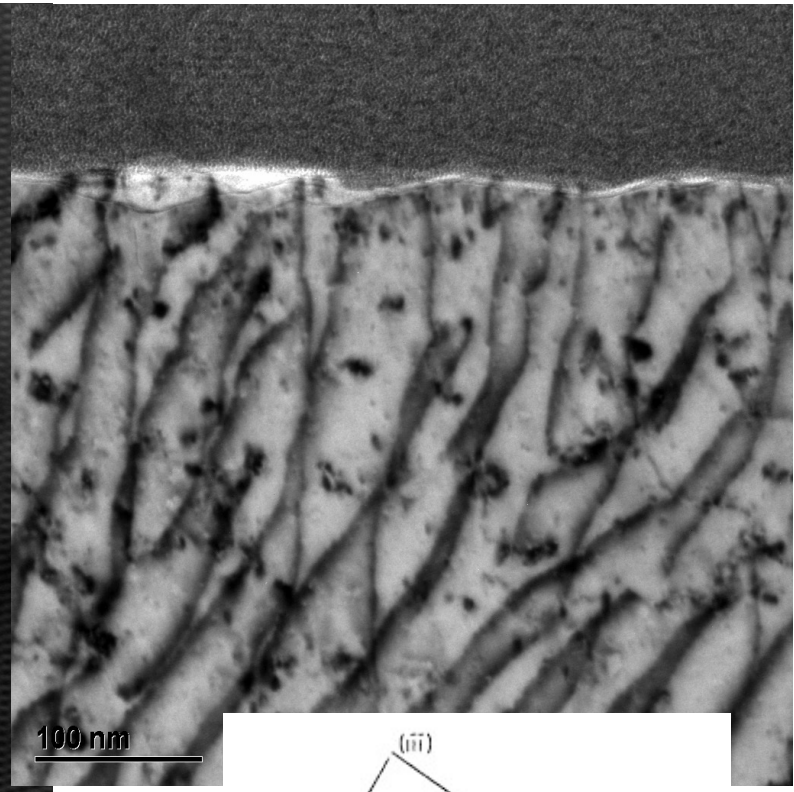
Eliyahu Zvi Engelberg,[1] Jan Paszkiewicz,[2] Ruth Peacock,[2] Sagy Lachmann,[1] Yinon Ashkenazy,[1,*] and Walter Wuensch[2]

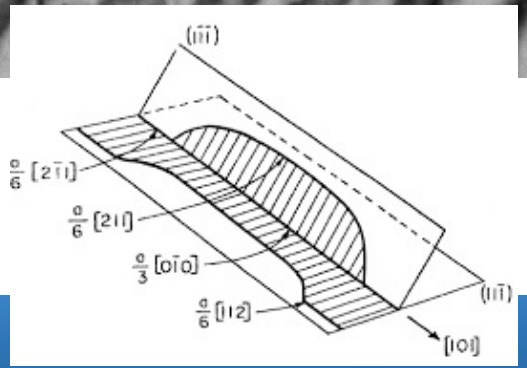
High res TEM: high dislocation density

- Expected mixed dislocations and stacking faults





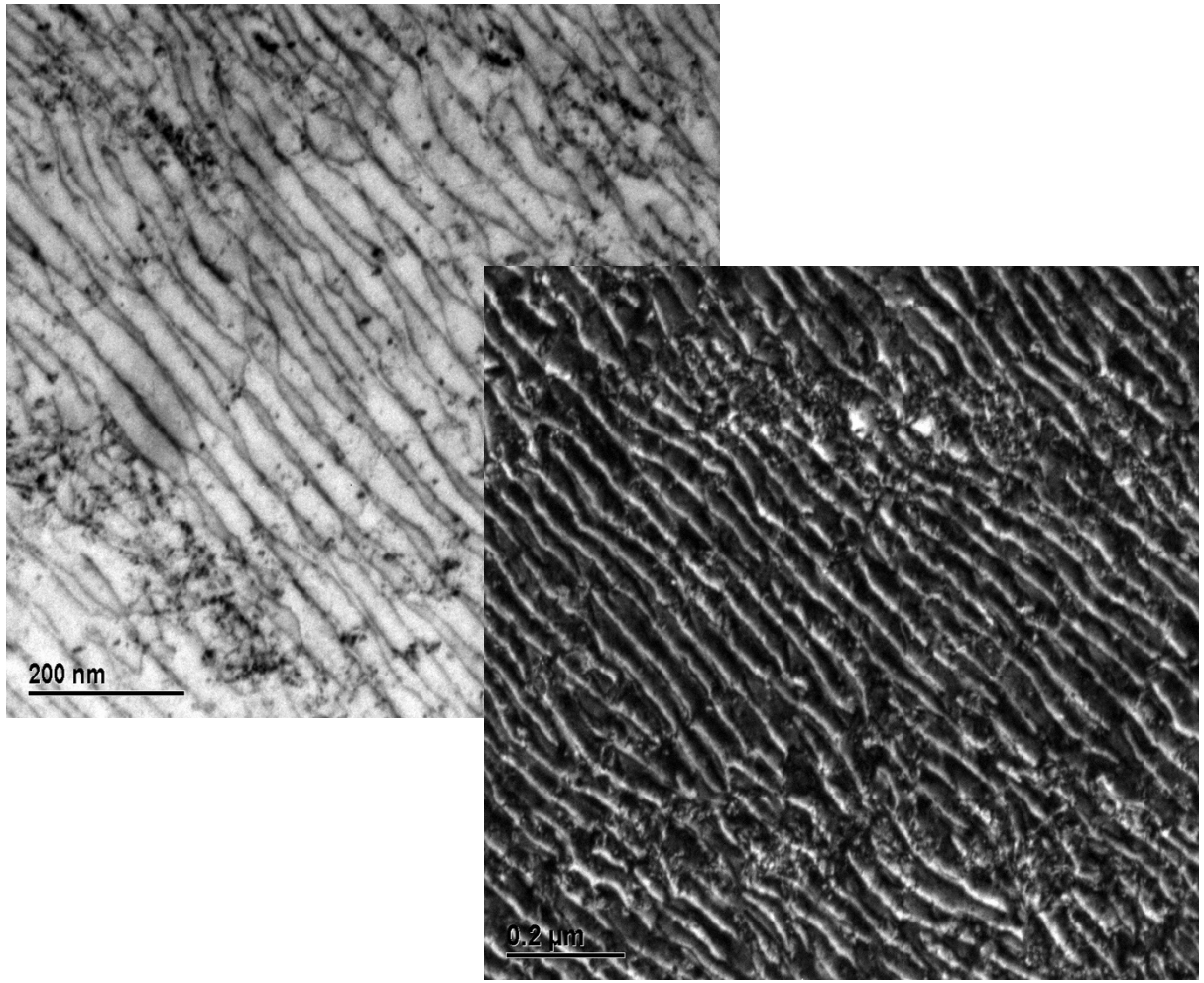




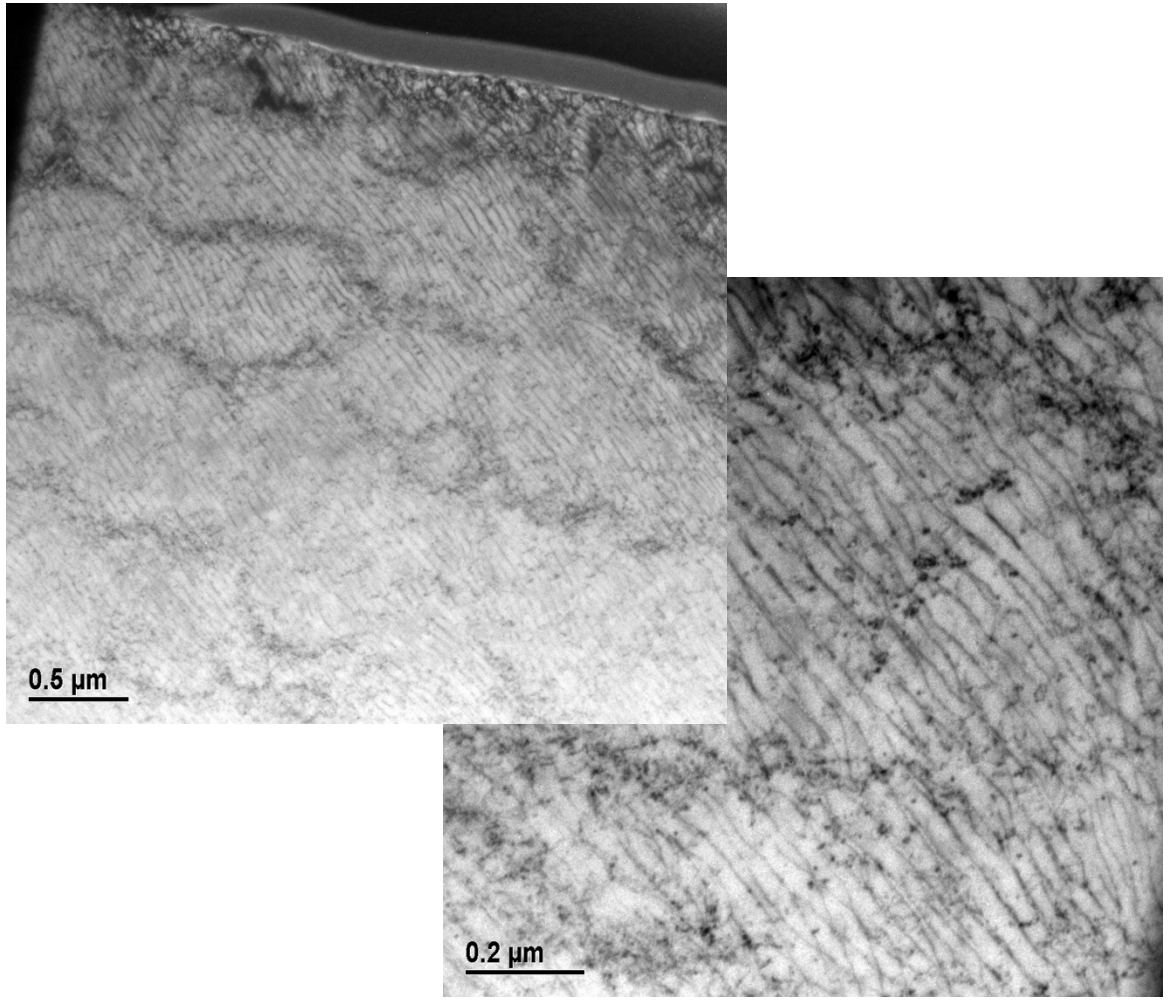
Two identical groups of defects released to the surface to form terraces

More details on dislocations characteristics

- Dissociated structures and constrictions

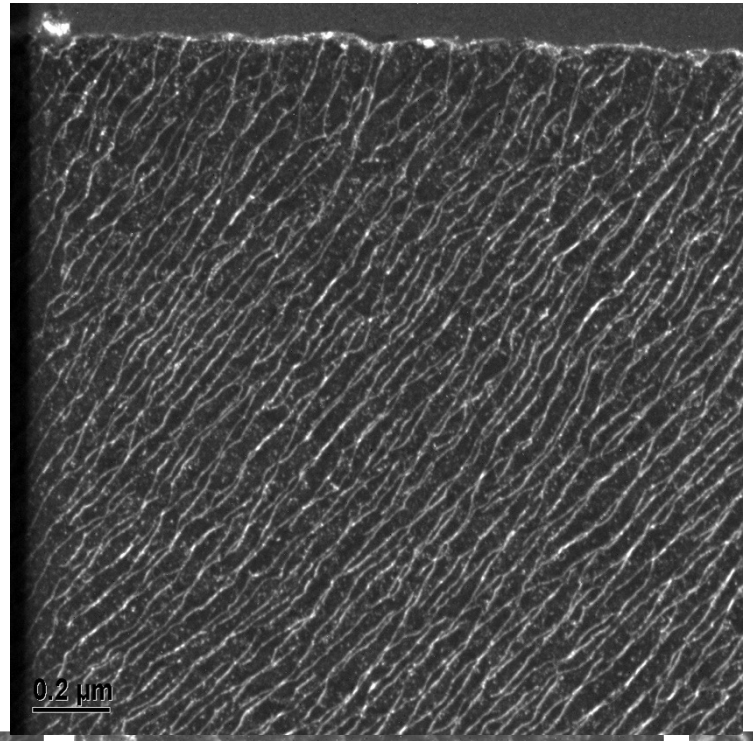


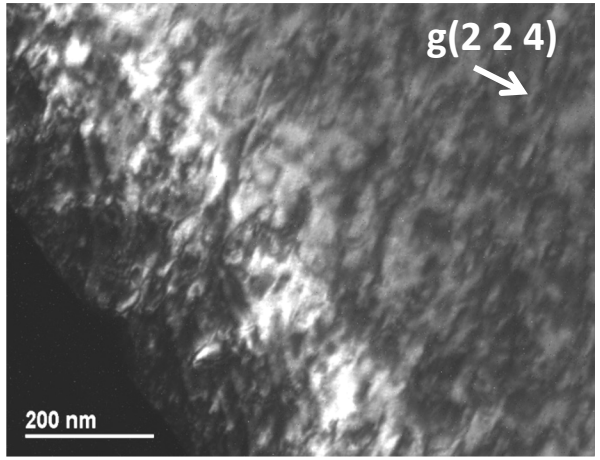
- Cellular structures

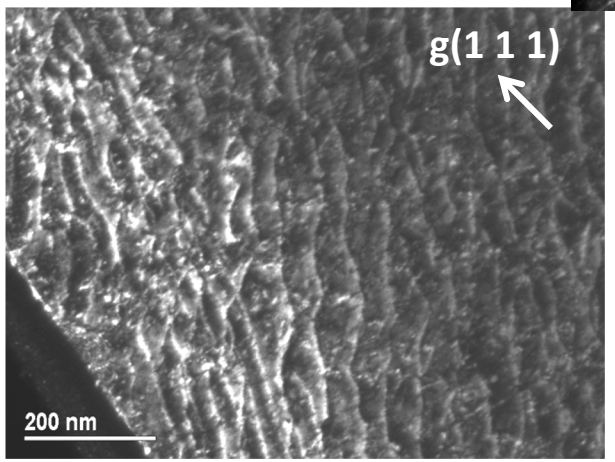


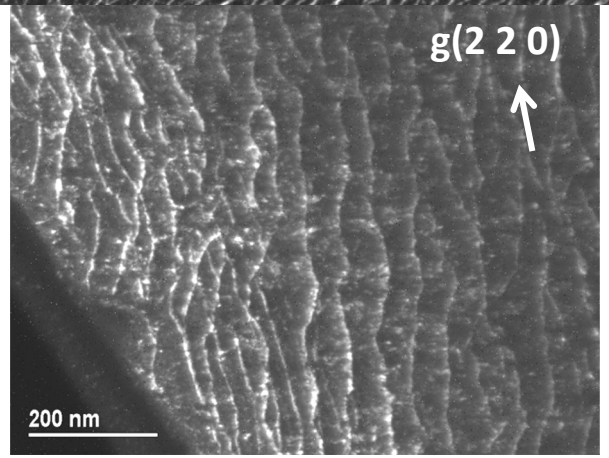
Quantifying dislocations properties

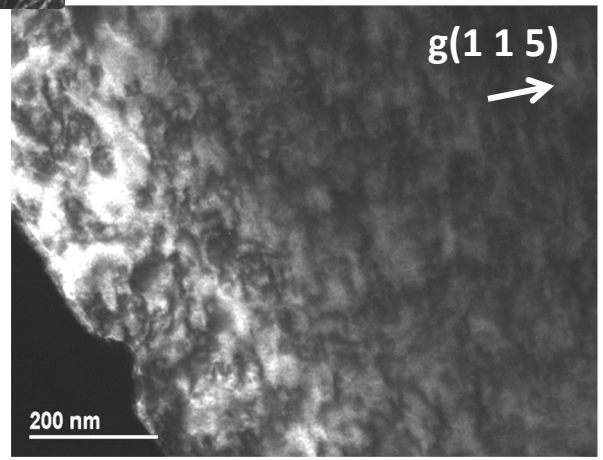
- Large grains with uniform dislocations patterns
- Normal density, but extremely coherent.
- Using various two-beam conditions dislocations identified as b=[110]
- Expected Edge and screw components for a dissociated mobile dislocation



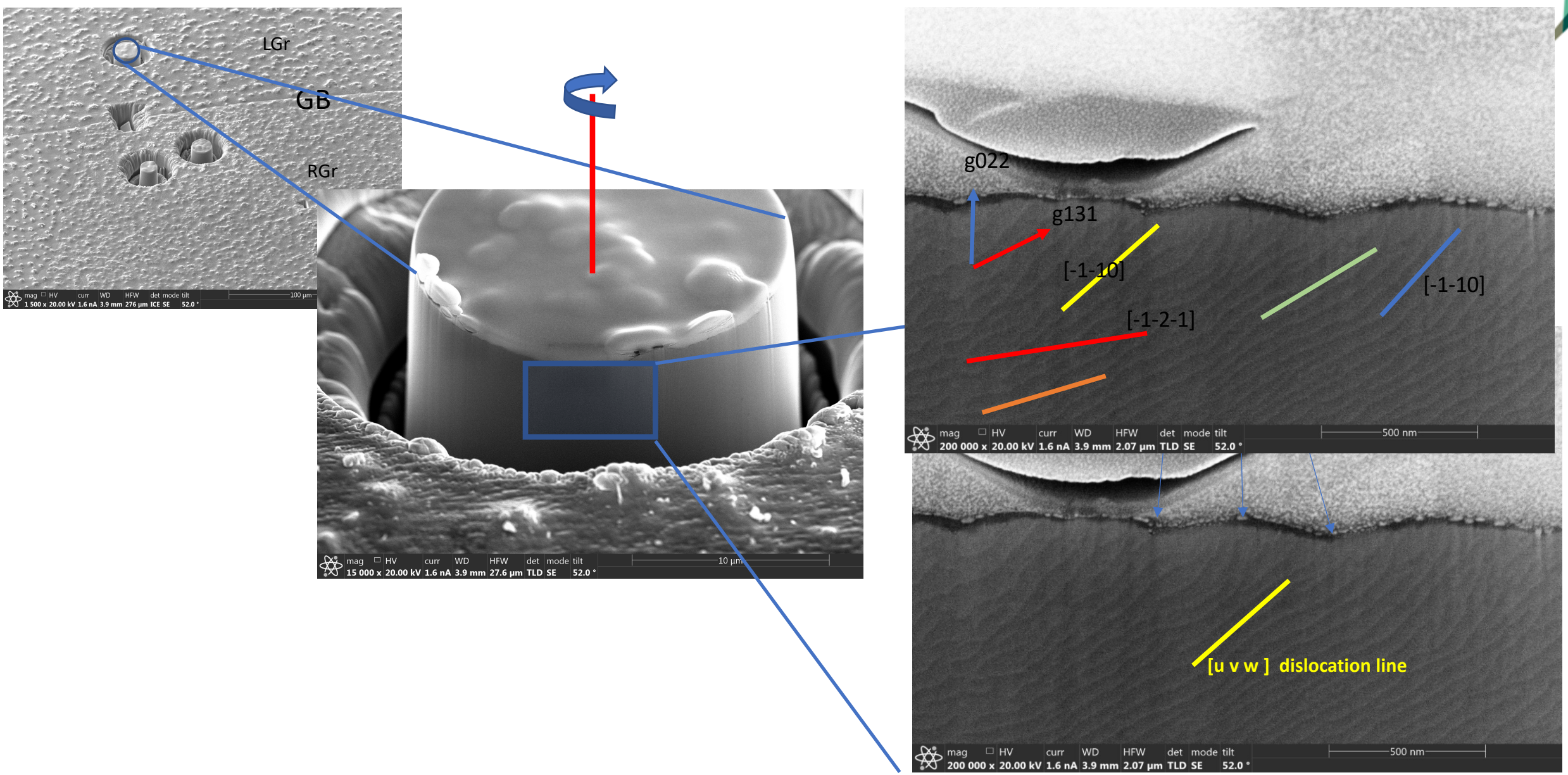






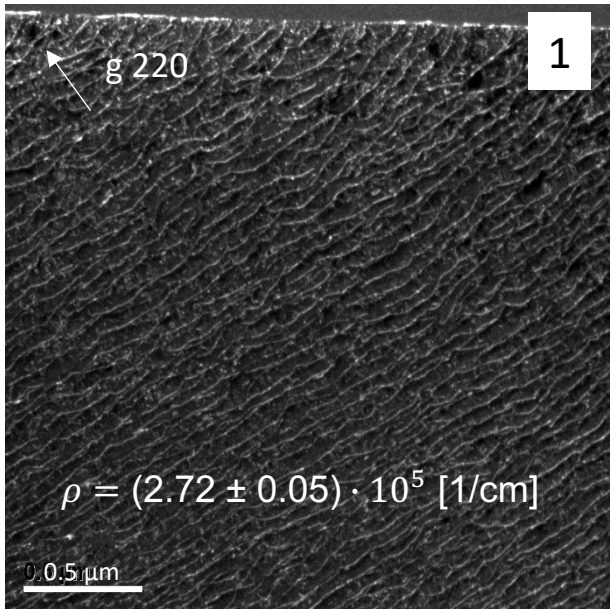


ECCI image of a column wall in LGr

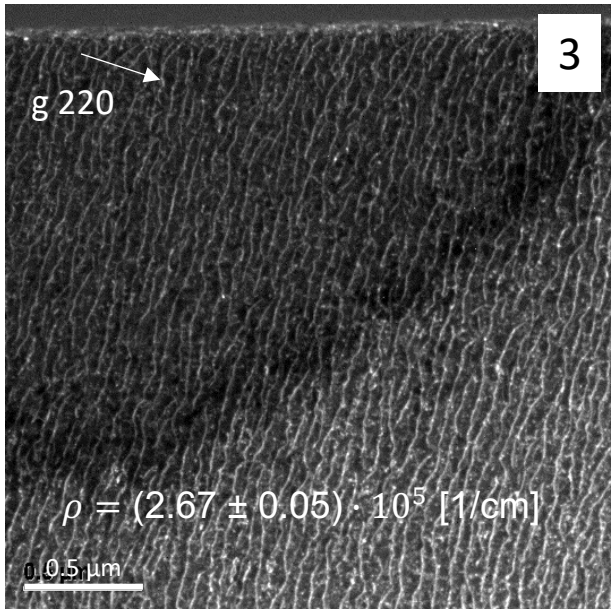


Dislocation density is not modified by conditioning

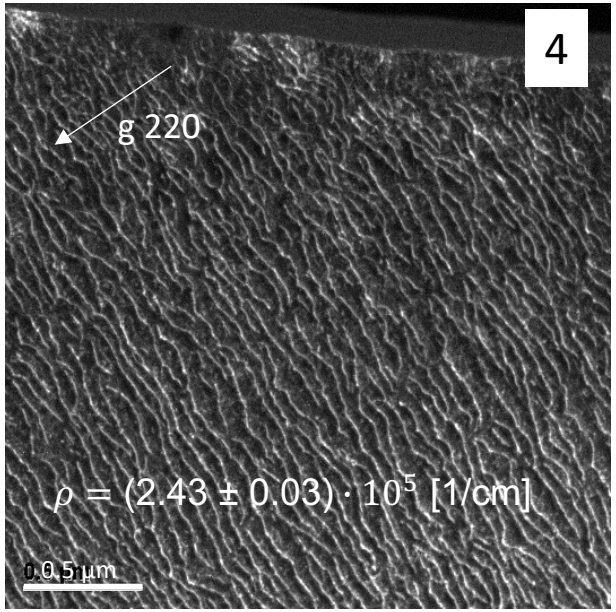
Reference



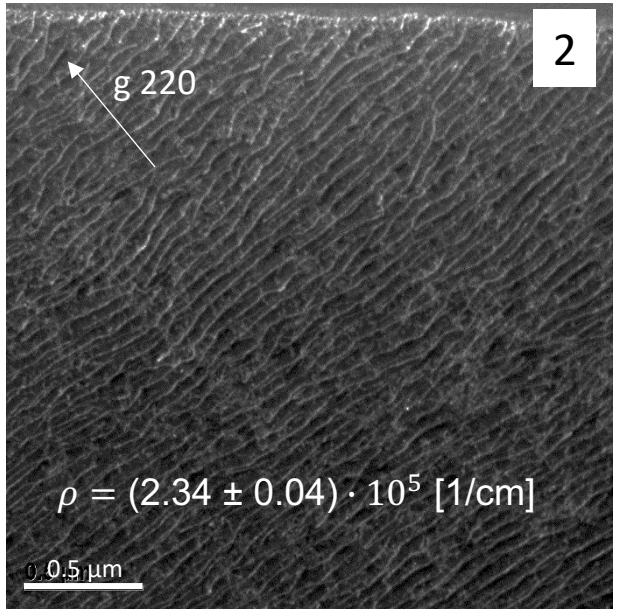
FA half conditioned



FA full conditioned

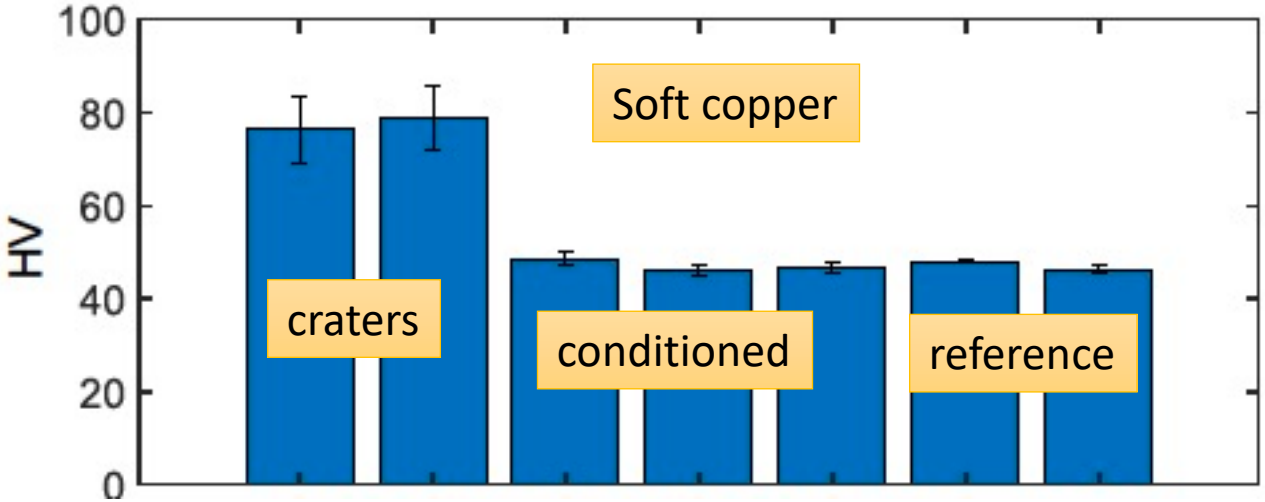


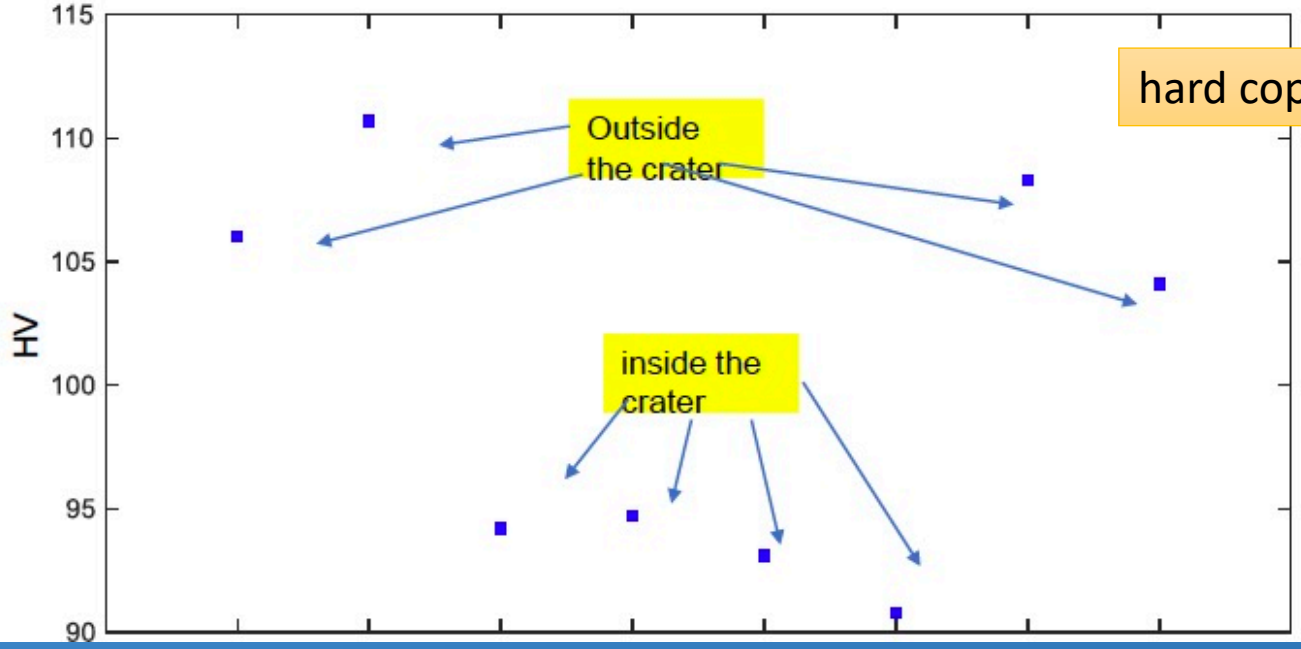
RF (Crab-cavity sample)

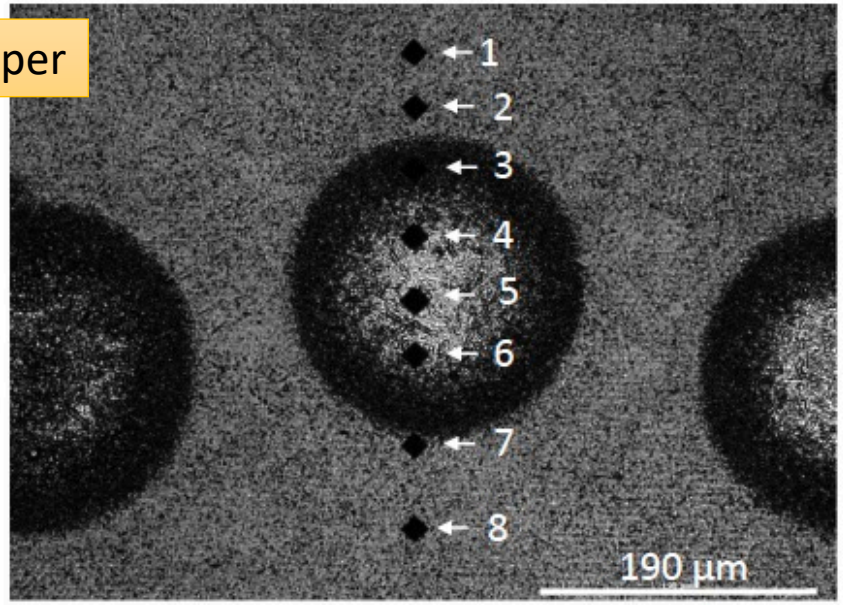


Surface Hardness is not modified by conditioning

- No clear hardness – conditioning correlation
- Softer regions in hard Cu
  - would have lead to repeat BD.
  - Should have seen a strong difference in bd locations correlation



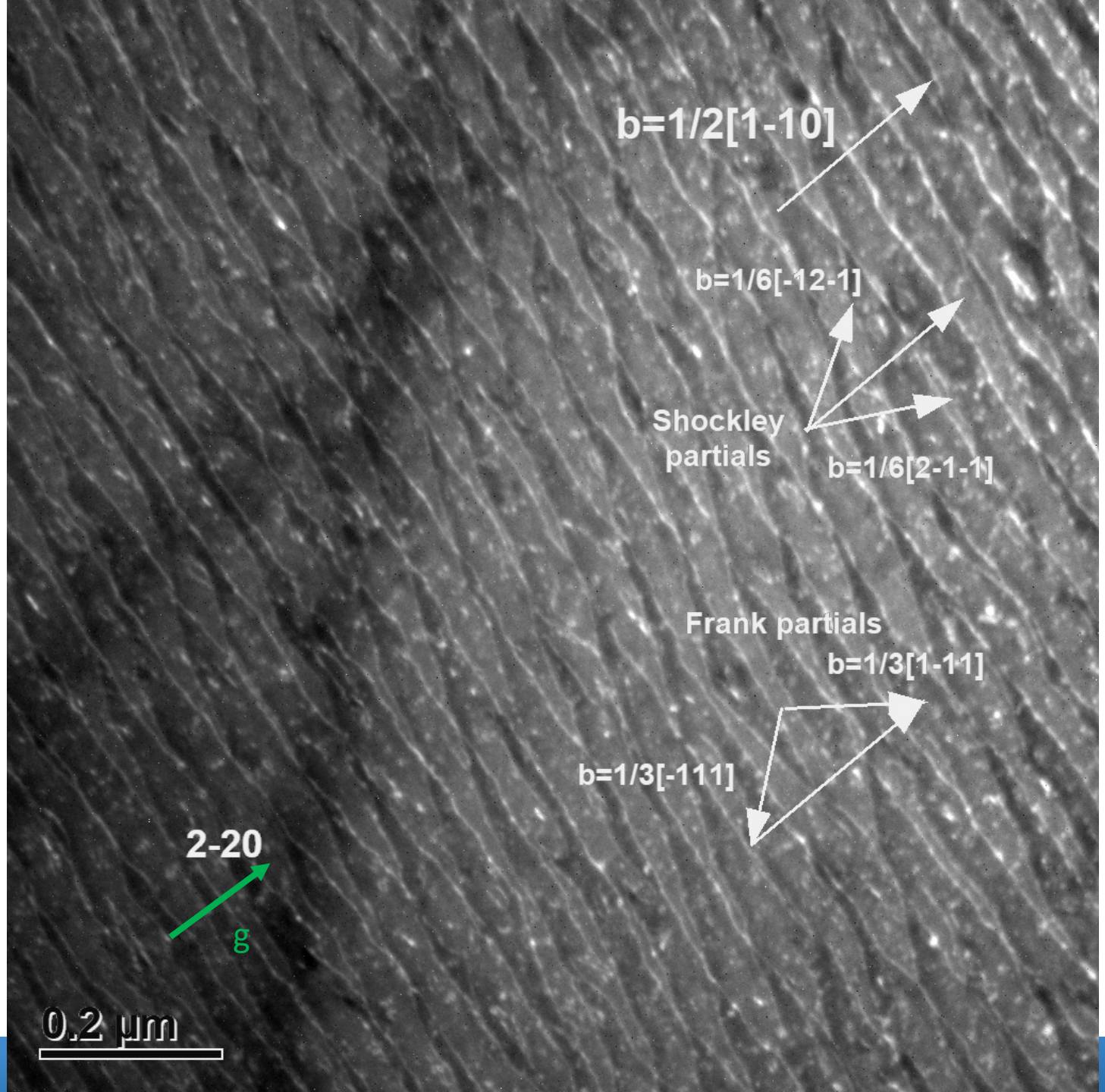


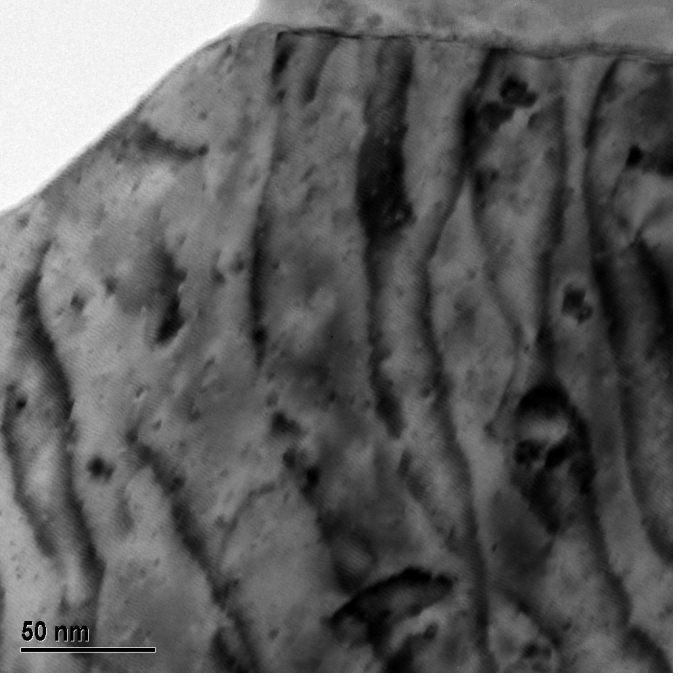


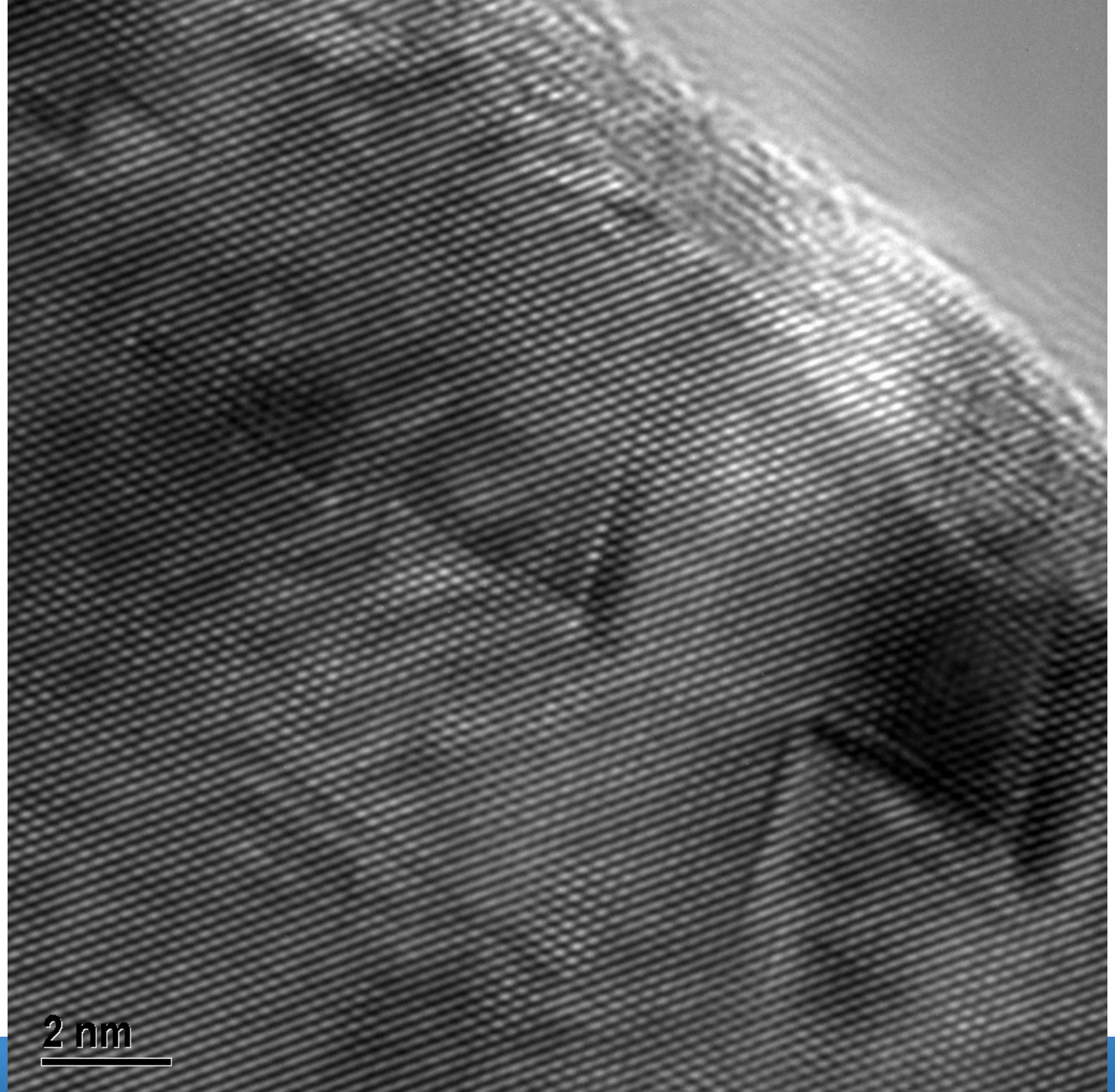
High dislocation density – no conditioning effect

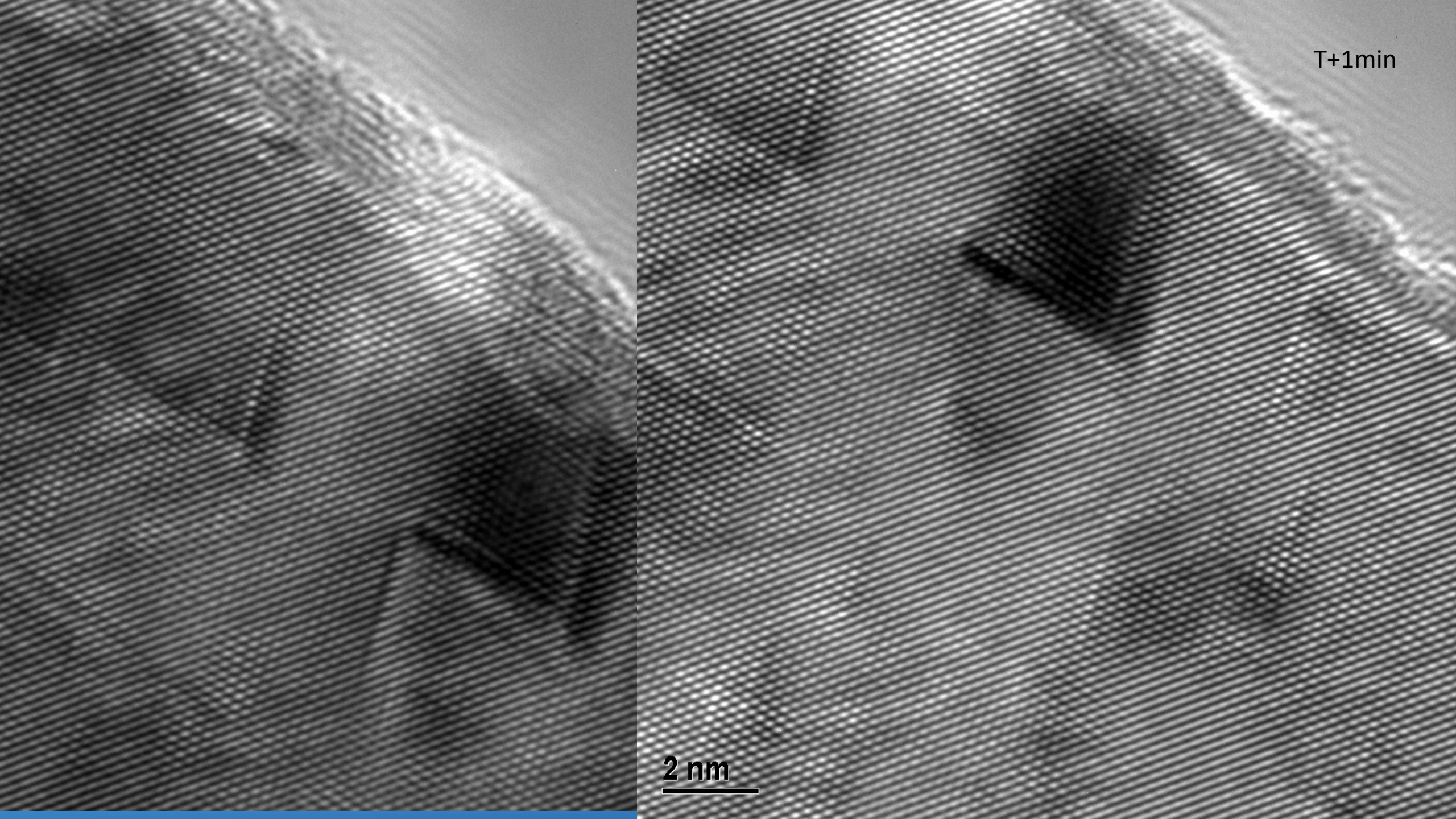
- Dynamics is consistent with a plastic dislocation-based mechanism.
- Conditioning process -
  No observable variation in dislocation density
  No observable variation in Surface hardness

  The universality of the observed structure and the fact it is agnostic to the high filed history and conditioning process leads to the proposition that it is not related to the conditioning process.
  And that conditioning is the process of removal of other possible sources of breakdown.

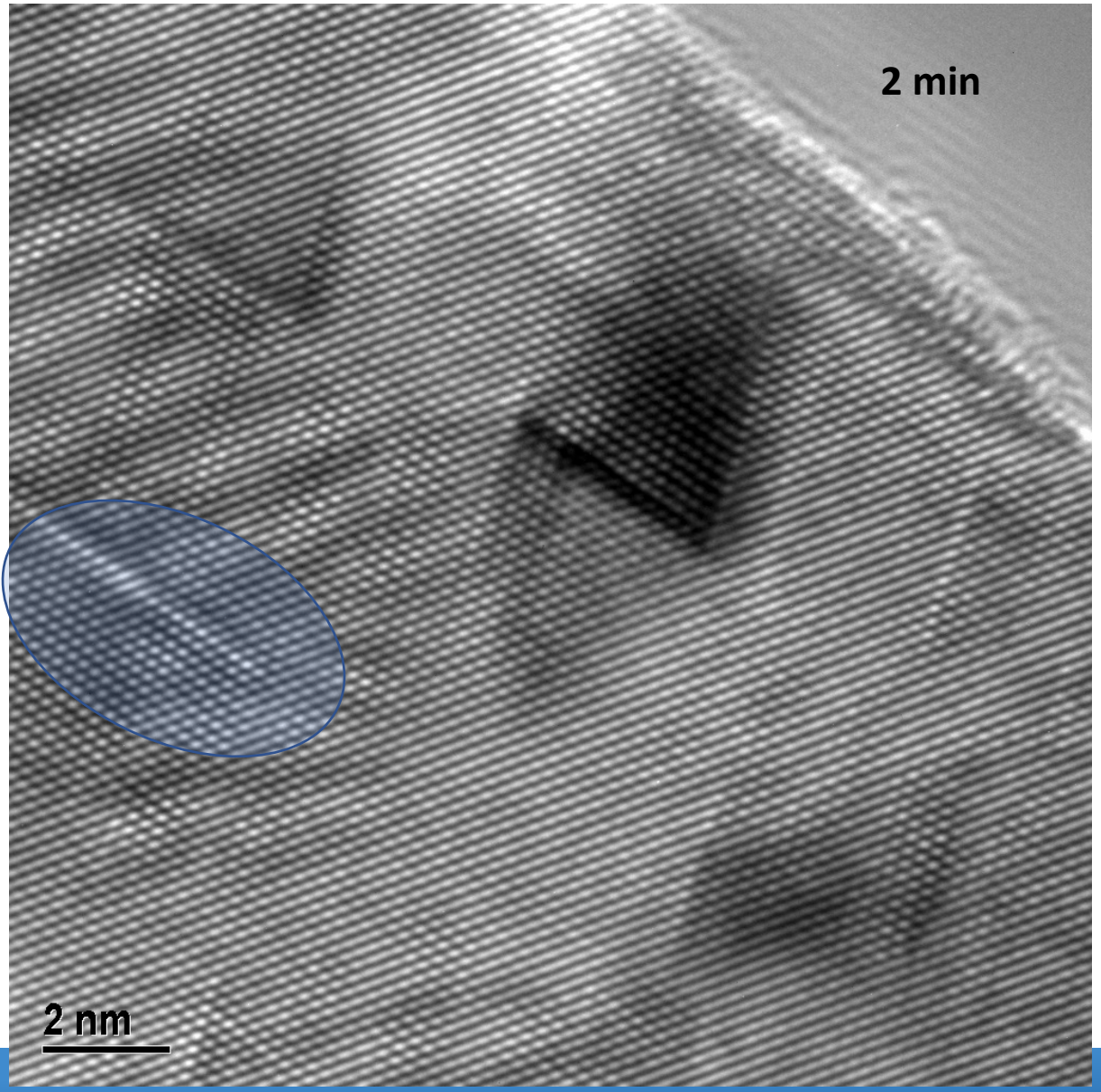

b=1/2[1-10]
b=1/6[-12-1]
Shockley partials
b=1/6[2-1-1]
Frank partials
b=1/3[1-11]
b=1/3[-111]
2-20
g
0.2 µm

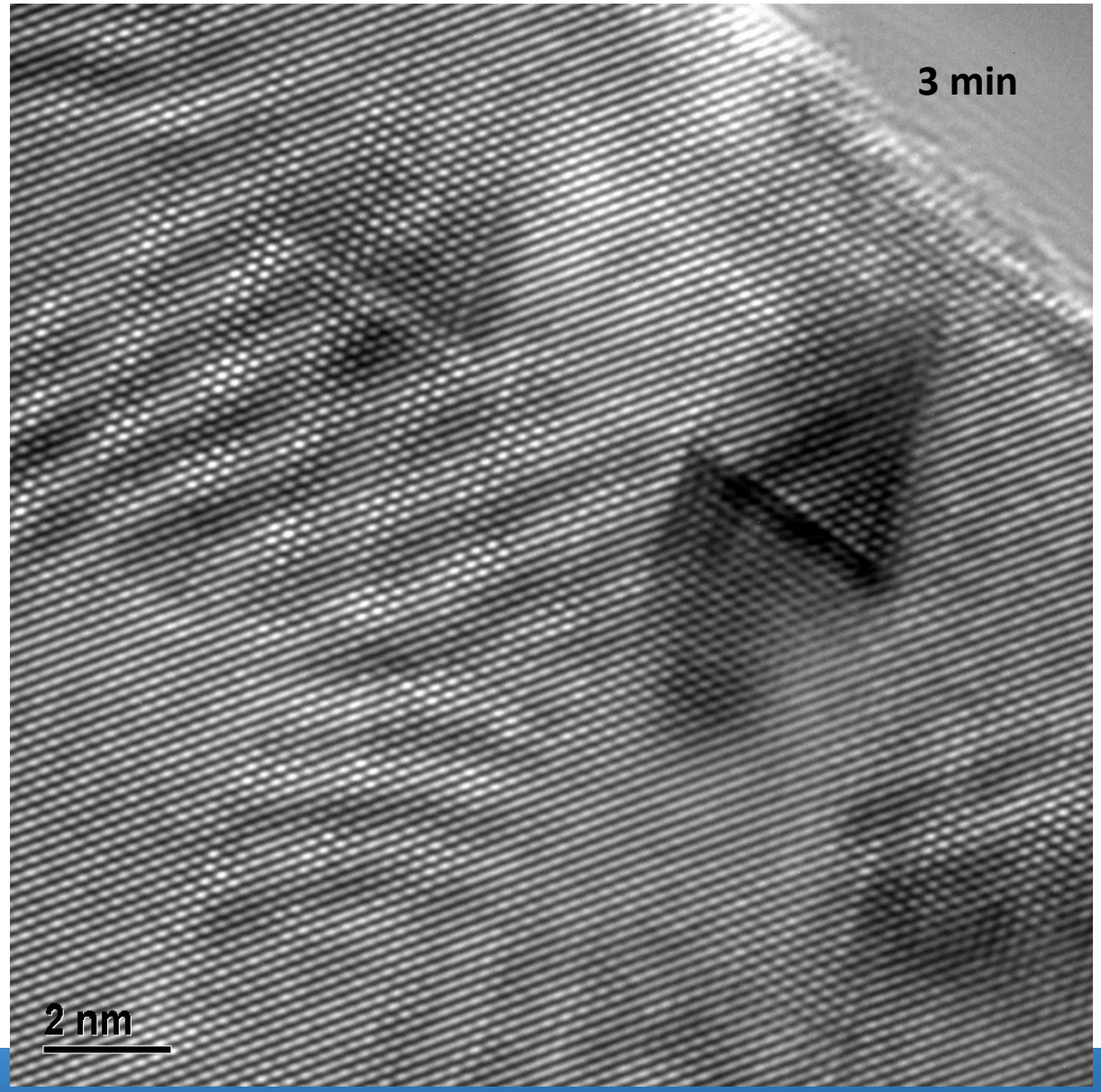

50 nm


2 nm

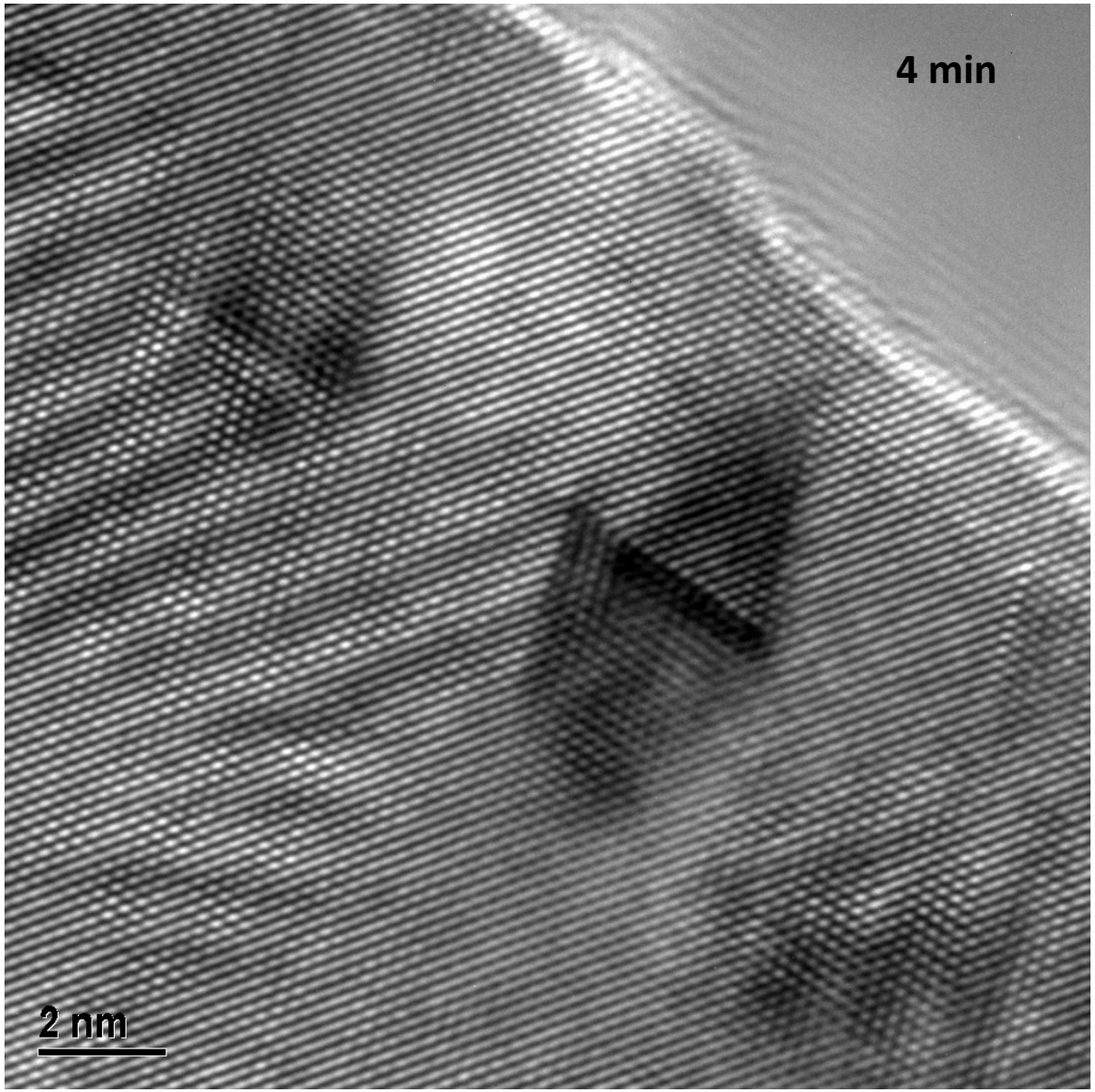

T+1min
2 nm

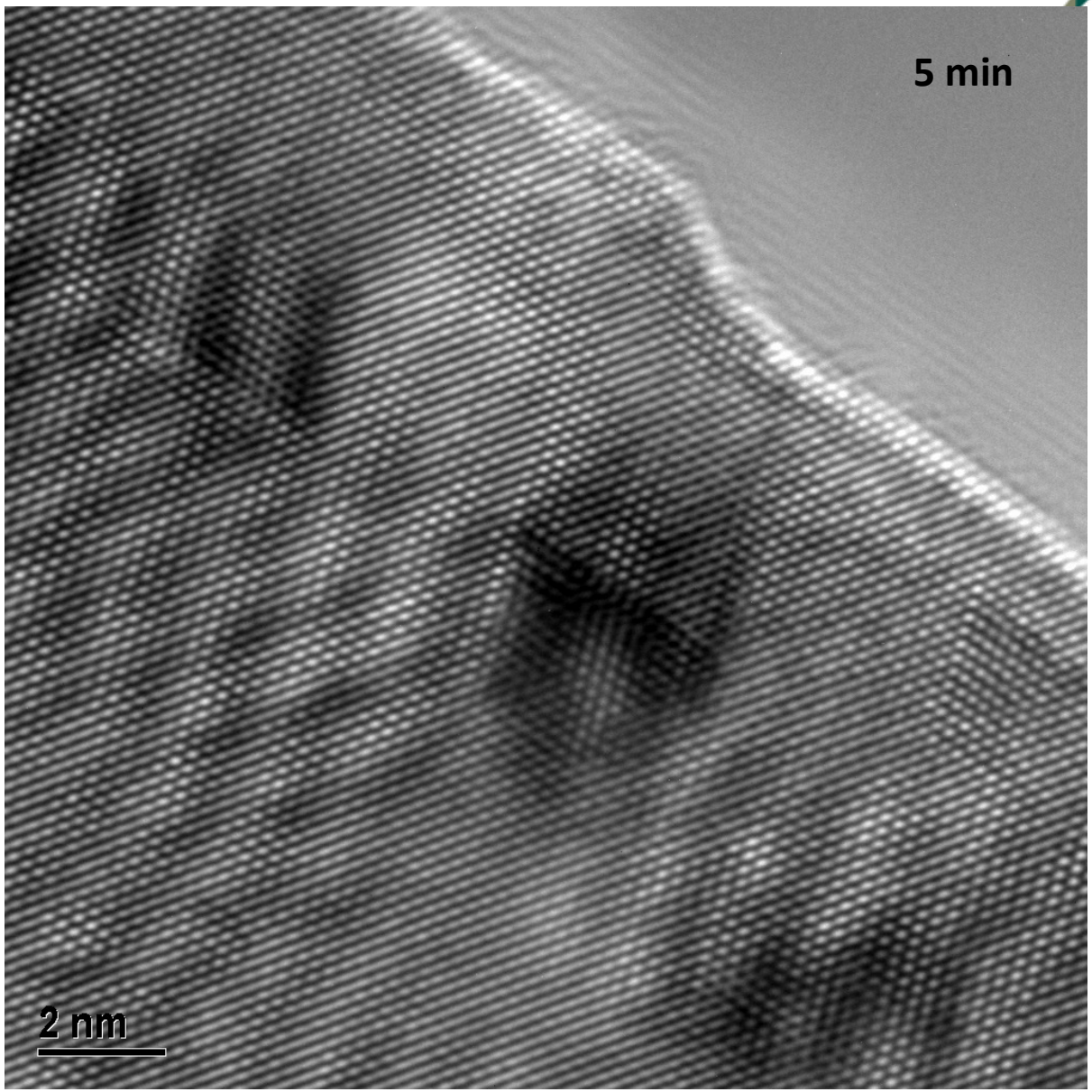
In situ observation : defects relax at free surface





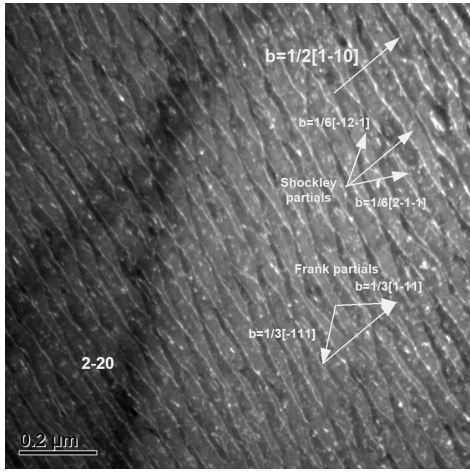
In situ observation : defects relax at free surface





Summary and Outlook

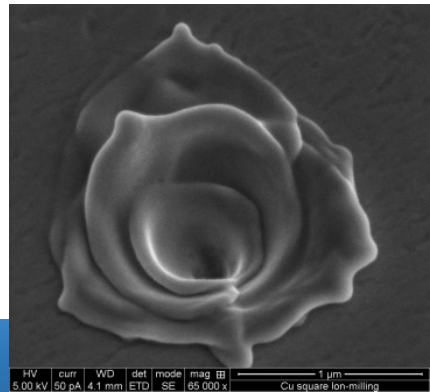
- Electrodes maintain a highly ordered dislocations array.
- Proposed a direct link between plastic mechanism and BD nucleation:
  - Consistent description of observed variation of BD rates.
  - Consistent with observations of high density of mobile dislocation sources.
  - Consistent results for critical rare fluctuations in dark currents.



- Conditioning – partially, process of removing extrinsic sources.

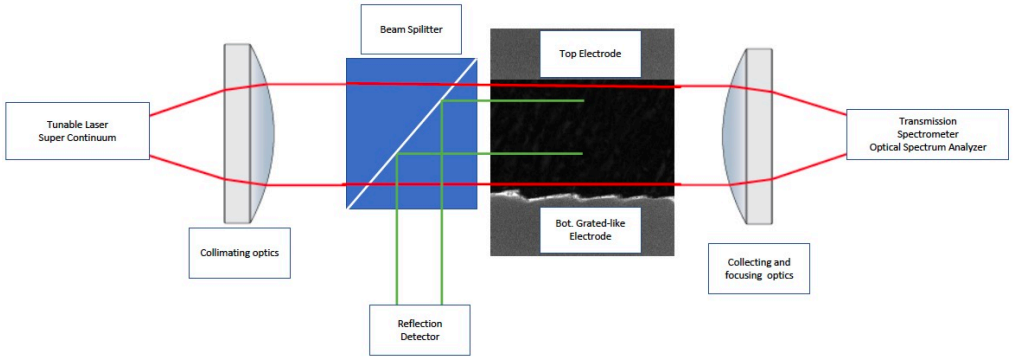
- How can we modify the intrinsic propensity for holding high gradients?
  By aiming at modifying the basic properties of the electrode material.

- Still missing the link between dislocation motion and plasma formation



Basic concept for optical diagnostics for plasmonic-work function analysis

- Aiming at a new optical setup



- Manufactured acoustic resonator on the surface (grating)
- Aim at measuring: absorption spectra (plasmons?) as well reflection indicating surface evolution under external field.