Theory of Electric Field Breakdown Nucleation: Mobile Dislocation Population Dynamics and Atomic Simulations

Yinon Ashkenazy   Inna Popov   Ayelet Yashar
Michael Assaf   Eli Engelberg

Hebrew University of Jerusalem

Padova, September 18, 2019

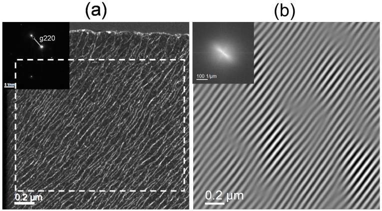
Overview

- Description of the mobile dislocation density fluctuations (MDDF) model.
- Predictions and proposals of future experiments.
- Plans for further work.

E.Z. Engelberg, Y. Ashkenazy, and M. Assaf, PRL **120**, 124801 (2018)

E.Z. Engelberg, A. Badichi Yashar, Y. Ashkenazy, M. Assaf, and I. Popov, PRST-AB **22**, 08351 (2019)

Dislocations



(a) TEM image of a soft OFHC Cu sample, and (b) a Fourier filtered image.

Dislocations are inherent in metallic samples.
Mobile dislocations are created in response to mechanical stress, gliding along high-density preferential planes. They become sessile when colliding.

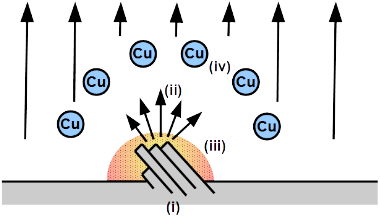
Breakdown is nucleated as a result of

(i) surface modification, leading to

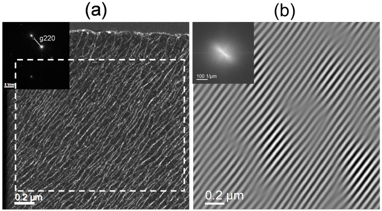
(ii) electric field enhancement, leading to

(iii) surface heating, leading to

(iv) formation of plasma, and subsequent arcing.



Dislocations



(a) TEM image of a soft OFHC Cu sample, and (b) a Fourier filtered image.

Dislocations are inherent in metallic samples.
Mobile dislocations are created in response to mechanical stress, gliding along high-density preferential planes. They become sessile when colliding.

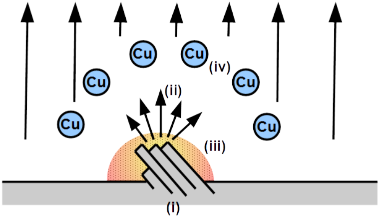
Breakdown is nucleated as a result of

(i) surface modification, leading to

(ii) electric field enhancement, leading to

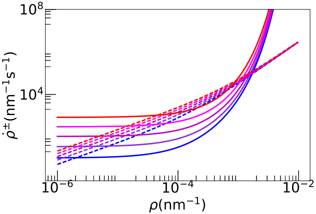
(iii) surface heating, leading to

(iv) formation of plasma, and subsequent arcing.

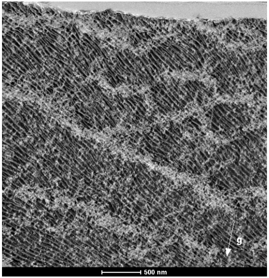


Stochastic Model

Under stress, dislocations tend to organize themselves in cells. The creation or depletion of one mobile dislocation corresponds to a discrete change of $\Delta\rho$ in the mobile dislocation density ρ in one cell.



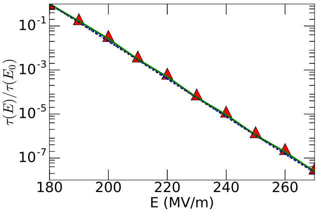
$\dot{\rho}^+$ (solid lines) and $\dot{\rho}^-$ (dashed lines) for five electric fields (bottom to top): 150, 190, 230, 270, and 310 MV/m.



STEM image from a fully-conditioned OFHC soft Cu electrode, showing dislocation cells.

We propose that breakdown nucleates when ρ reaches ρ_c, leading to a critical transition in the mobile dislocation density.

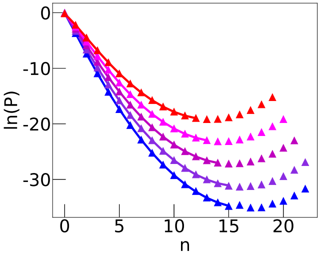
Results of the Model



The mean breakdown time τ is found to depend exponentially on the electric field:

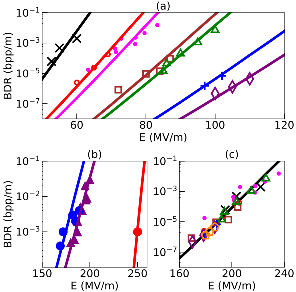
$$\tau \simeq \mathcal{C} e^{1-E/E_0}$$

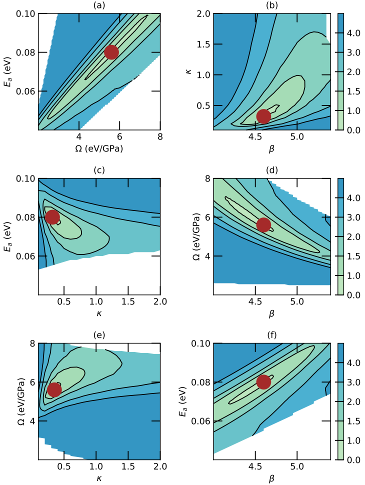
The *quasistatic probability distribution* (QSD) describes the probability of finding the system in state $n = \rho/\Delta\rho$ at any moment prior to the critical transition.



QSD for electric fields of 180, 200, 220, 240, and 260 MV/m (from bottom to top).

Comparison to Experiment



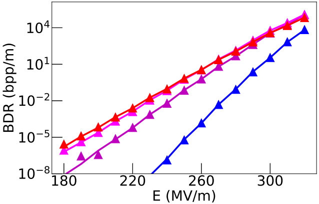


Four parameters are not known from *a priori* physical considerations. We use a least squares algorithm to fit them to experiments.

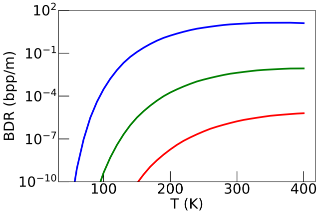
Temperature

Experiments measuring the BDR as a function of temperature can provide better estimates of the activation energy and volume, E_a and Ω.

$$\dot{\rho}^{+} \sim e^{-\frac{E_a - \Omega\sigma}{k_B T}}$$



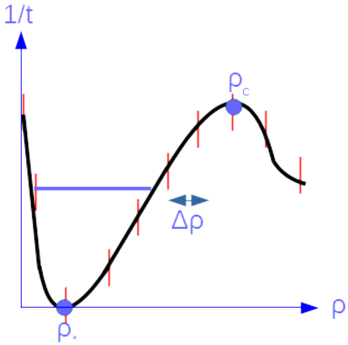
BDR as a function of the electric field for temperatures of (bottom to top) 100, 200, 300, and 400 K.



BDR as a function of the temperature for fields of (bottom to top) 180, 220, and 260 MV/m.

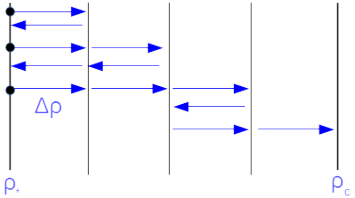
The effect of the temperature is the most pronounced for weaker electric fields, because the stronger the electric field is, the greater the stress and therefore the lower the activation enthalpy is, thus making the temperature less significant.

Pulse Length – Trajectories

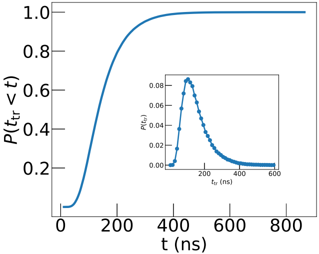


The slip-plane system normally fluctuates around ρ_*. The random walk is a birth-death Markov Process.

It can be described as a series of attempts to propagate from ρ_* (stable ρ) to ρ_c (critical ρ). Only the last attempt is successful.

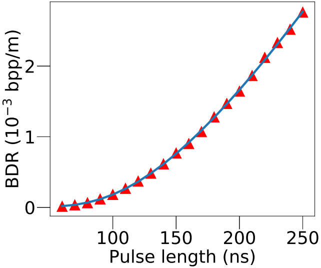


Pulse Length – BDR Dependence



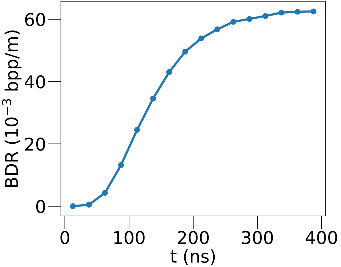
For pulse lengths on the order of t_{tr} (or shorter), a significant number of trajectories, which would have reached the critical point, will rapidly go to $n = 0$ once the field is switched off. Therefore, in this regime, we expect a strong dependence of the BDR on the pulse length.

t_{tr}, the time it takes to reach the critical point $n = n_c(E)$ starting from $n = n_*(E)$, has a sigmoid CDF. This distribution does not change much in the range of interest of electric fields.



Distribution Within Pulse

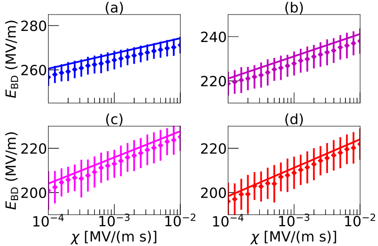
Under the assumption of pulse independence, the distribution of breakdowns in time within each pulse should be an increasing function, due to the finite evolution time t_{tr}.



Probability of a breakdown occuring as a function of the time within the pulse. The probability distribution is presented as a histogram of sixteen bins, each bin 25 ns wide, and normalized by the total BDR.

If the system does not reach full relaxation between pulses, we expect the BDR to depend on the duty cycle of the pulses, rather than solely on the pulse length.

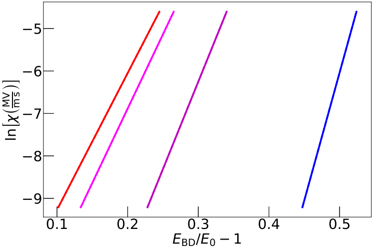
Field Ramping



Mean breakdown field as a function of the field increase rate for a linearly incrementing field, for temperatures of (a) 100, (b) 200, (c) 300, and (d) 400 K.

Increasing the electric field at a constant rate χ leads to a corresponding mean breakdown field $E_{\mathrm{BD}}(\chi)$. The relation of E_{BD} to χ can be used to find γ.

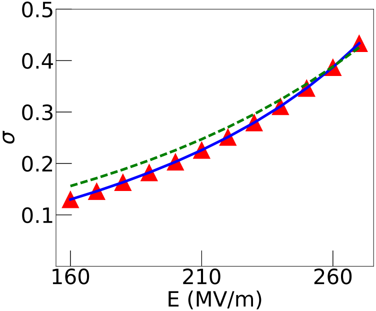
This procedure is analogous to the Kissinger method for finding the activation energy of a chemical reaction. It provides a faster and more accurate method of measuring γ.



Kissinger-like plot for temperatures of (lines from right to left) 100, 200, 300, and 400 K.

Fluctuations

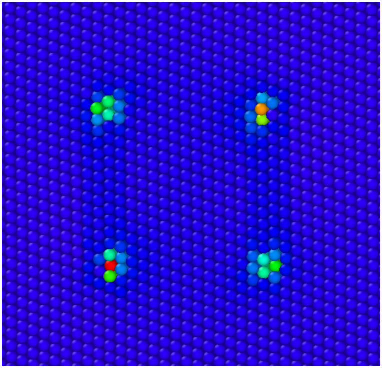
- The standard deviation of the QSD is found to be an increasing function of the electric field.
- This increase with field may be observed experimentally, by measuring acoustic emission signals, or by measuring the dark current between the cathode and anode as a function of the applied electric field.

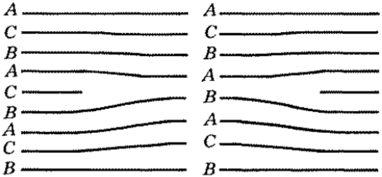


- This would allow the development of methods to detect early warning signals of imminent breakdowns.

Plans for Further Work

Molecular dynamics simulations of dislocation arrays.

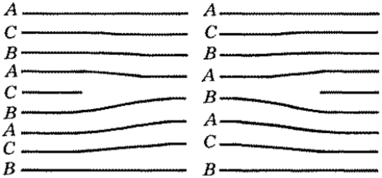




- How are mobile dislocations created and depleted?
- How can we control these processes? Can we modify them to our benefit?

Plans for Further Work

Molecular dynamics simulations of dislocation arrays.



- How are mobile dislocations created and depleted?
- How can we control these processes? Can we modify them to our benefit?

eli.engelberg@mail.huji.ac.il

Summary

- Simple model with a critical transition and a stochastic mechanism for BD nucleation.
- Material-dependent constants inferred from microscopy, and parameters found from fit to experiments.
- Predictions made for a variety of possible measurements.
- Model outlook: inter-cell correlation, analysis of the nucleation process.