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.


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 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.
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 $\rho$ in one cell.

We propose that breakdown nucleates when $\rho$ reaches $\rho_c$, leading to a critical transition in the mobile dislocation density.
The mean breakdown time $\tau$ is found to depend exponentially on the electric field:

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

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 \textit{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 $\Omega$.

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

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.
The slip-plane system normally fluctuates around $\rho_\ast$. The random walk is a birth-death Markov Process.

It can be described as a series of attempts to propagate from $\rho_\ast$ (stable $\rho$) to $\rho_c$ (critical $\rho$). Only the last attempt is successful.
$t_{tr}$, 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.

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.
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 $t_{tr}$.

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

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

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 $\gamma$.

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.

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