The Effect of Combined Thermal Stresses and Electric Fields on the Formation of RF Breakdown Precursors

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Abstract

Experimental evidence often leads to a hypothesis that breakdown events are accompanied by elevated temperature and dark current spike due to high asperity nano-structure formation which significantly enhances the local electric field [1]. However, the mechanistic origin of such field enhancement under typical fields and heating conditions remains poorly understood. We built a model describing the evolution of a typical copper surface driven by an electric field and temperature.
Implementing a mesoscale curvature-driven diffusion model, we identify the critical regimes where electric fields, and thermo-elastic forces combine to lead to the spontaneous formation of sharp surface features. These regimes strongly resonate with previous experimental findings on breakdown of copper electrodes, suggesting surface diffusion to be playing critical role in breakdown precursor formation.

Computational Flowchart

1 Create the mesh for vacuum and material
2 Solve the thermal stress and strain tensor
3 Calculate strain-energy density
4 Solve the local field distribution
5 Calculate the Electric field energy density
6 Solve for new surface profile and update the mesh

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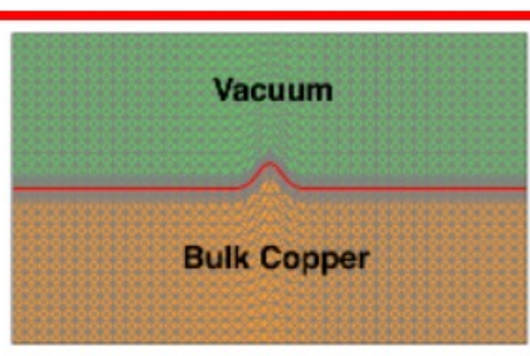
Finite Element Method



1. Local field distribution is solved on the vacuum mesh
2. Linear Thermoelasticity is solved on the copper mesh

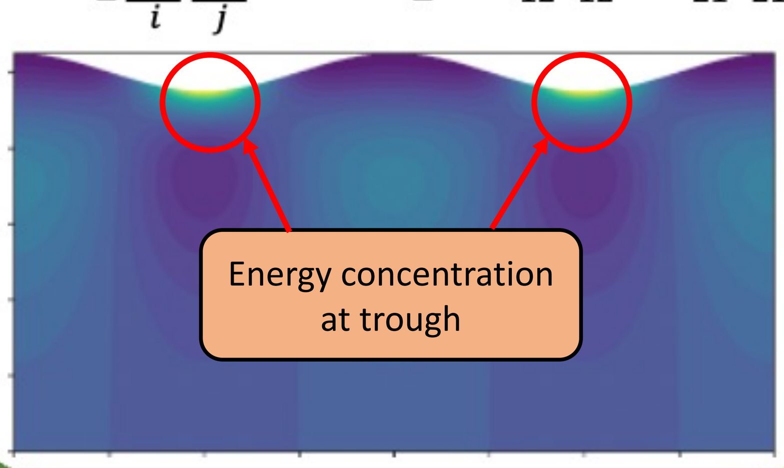
2 & 3

Linear Thermoelasticity

$$-\nabla\cdot\sigma(u)=0$$
$$\sigma(u)=\lambda tr(\epsilon(u))\mathbb{1}+2\mu\epsilon(u)-\frac{\alpha Y}{1-2\nu}\Delta T\mathbb{1}$$
$$\epsilon(u)=\frac{1}{2}(\nabla u+(\nabla u)^T)$$

Strain-Energy Density

$$\omega_T=\frac{1}{2}\sum_i^2\sum_j^2\sigma_{ij}\epsilon_{ij}=\frac{1}{2}\begin{pmatrix}\sigma_{11}\epsilon_{11}+\sigma_{22}\epsilon_{22}\\+\sigma_{12}\epsilon_{12}+\sigma_{21}\epsilon_{21}\end{pmatrix}$$



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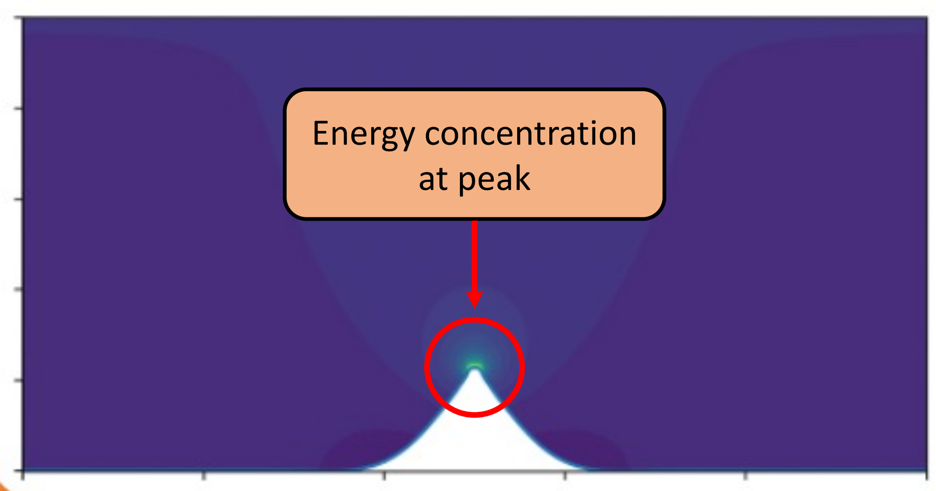
Electrostatic

$$\nabla\cdot(\nabla\phi)=0$$
$$E=-\nabla\phi$$

Field Energy Density

$$U_E=\frac{1}{2}\epsilon_0E^2$$



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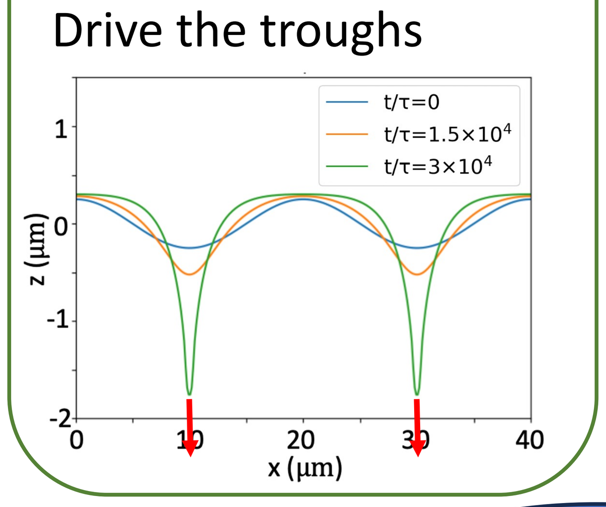
Surface Diffusion

$$V_n=\frac{D_s\Omega v_s}{k_bT}\frac{\partial^2\mu_c}{\partial s^2}$$
$$\frac{\partial h}{\partial t}=\frac{D_s v_s\Omega}{k_BT}\frac{\partial}{\partial x}[(1+h_x')^{-1/2}\frac{\partial}{\partial x}(\mu_c)]$$
$$\mu_c=\Omega(\gamma k-U_E+\omega_T)$$

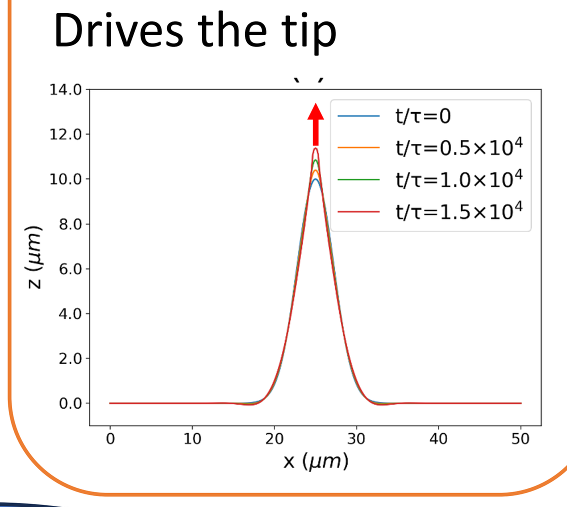
Chemical potential = surface tension + electrostatic energy + strain energy density

Simulation Result

Heating Effect
Drive the troughs

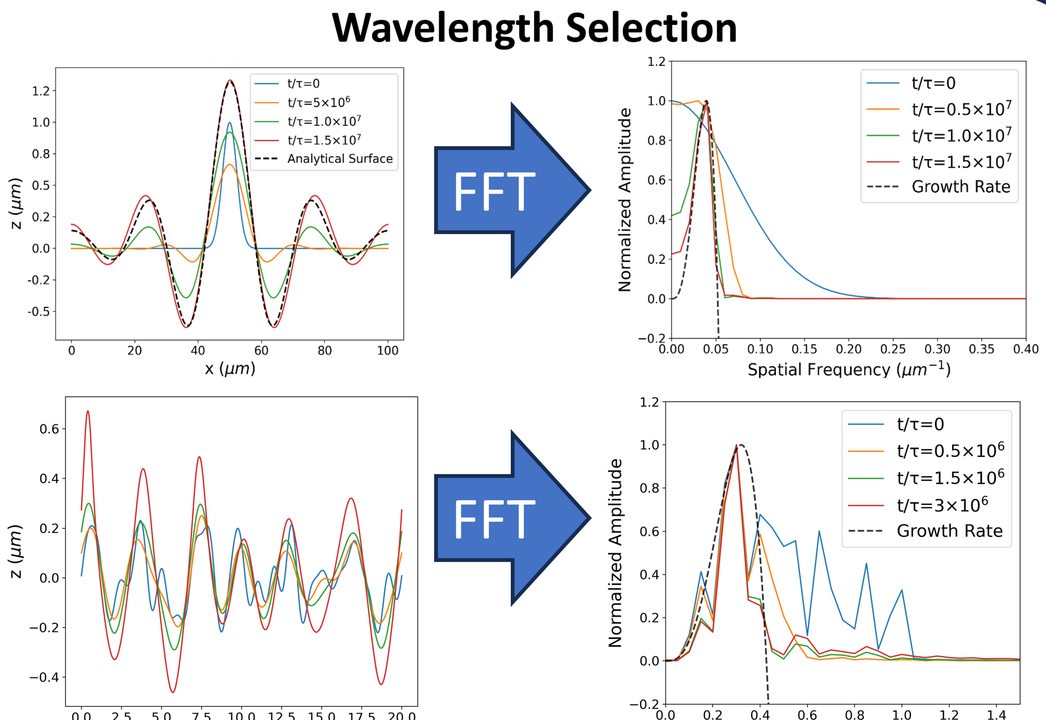


Electrostatic Effect
Drives the tip



Synergistic coupling

Wavelength Selection

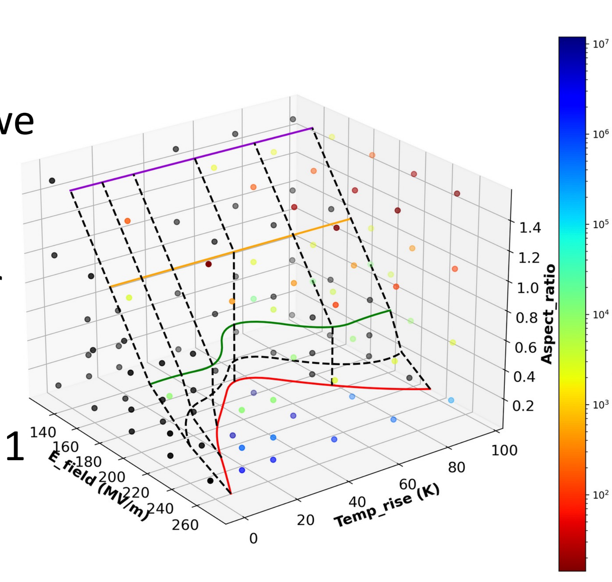


Critical Regime for Tip Instability

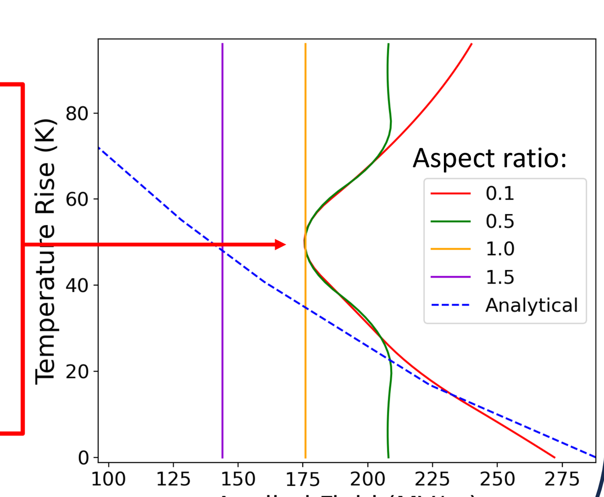
Applied Parameters

- $E_{applied}$ = 140-280 MV/m
- ΔT = 0-100 K

1.) At low aspect ratio < 0.1, we see temperature aids in tip growth.
a.) Optimal temperature for tip growth
2.) Limited temperature dependence at aspect ratio > 1



Comparable to experimental measurements [2]
$E_{applied}$ ≈175 MV/m
ΔT ≈ 50 K
Aspect ratio = 0.1



Conclusion

In this work, we demonstrated that metallic surface could undergo instability through surface diffusion under electric and thermally driven stress, and eventually lead to the formation of nanotip breakdown precursor. The curvature-driven surface diffusion mechanism is capable of describing precursor formation under conditions comparable to experimental observations in terms of applied field, temperature rise, and an initial surface profile. The numerical model results agree well with the analytical prediction from linear stability analysis within the small aspect ratio limits. Our results agrees with the experimental observation where copper crystal at (111) orientations are the most prone to breakdown precursor formation [4].

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