Stochastic growth of metal whiskers

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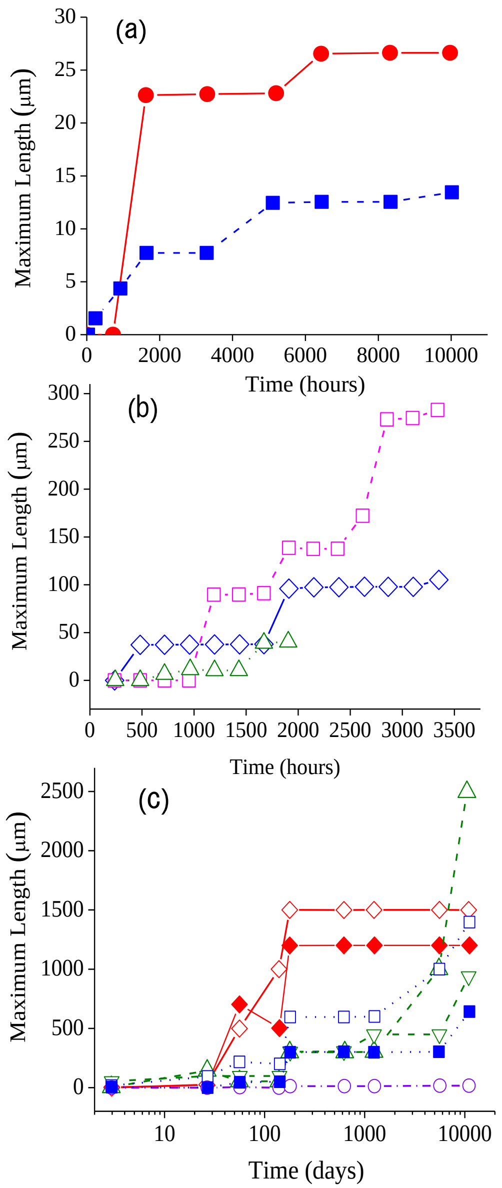
Outline

- Time dependent whisker growth, stop-and-go (intermittent) pattern
- Why the intermittent growth can be of interest practically and scientifically
- What makes whisker grow? A brief outline of existing theories
- The electrostatic theory: long whiskers are energetically favorable
- Growth in the random energy landscape: barriers and stopping times
- How we approached the intermittency statistics quantitatively
- Results, predictions, and recommendations

Stop-and-go (intermittent) whisker growth



K. S. Kim, S. S. Kim, S. J. Kim, K. Suganuma, Prevention of Sn Whisker Formation by Surface Treatment of Sn Plating Part II, ISIR, Osaka University, Masanobu Tsujimoto, Isamu Yanad, C. Uyemura Co., Ltd., TMS Annual Meeting (2008).

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M. A. Ashworth and B. Dunn , (2016), An investigation of tin whisker growth over a 32-year period, Circuit World, 42, 183 (2016).http://dx.doi.org/10.1108/CW-07-2015-0038

+ private communications from G. Davy and A. Kostic

Significance of intermittent growth pattern

- Practical:

  predictability compromised when a temporarily stopped whisker is counted as fully formed. Accelerated (limited time) testing of whisker propensity should account for the possibility of 'after-death' whisker growth and intermittent patterns. How often a whiskers length must be measured not to overlook a relatively short time intermittency?

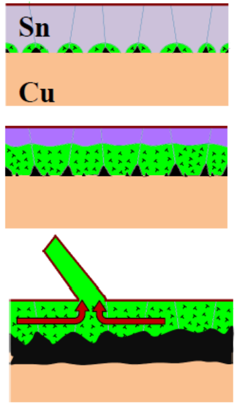
- Scientific:

  what is the nature of whisker growth stochasticity? Understanding of metal whisker growth should include factors of random nature. Metal whiskers appear to be an object of the physics of disordered systems, call upon statistical description.

What makes whiskers grow?
A brief outline of existing theories: it is stress

E. Chason et al 2010: stress

Summary - Mechanisms of whisker growth



1) Cu diffuses into Sn to form IMC
2) IMC grows → stress spreads through Sn
   - *dislocation motion/point defects*
3) Oxide prevents defect annihilation at surface
   – *stress builds up in layer*
4) Stress causes yield of "weak" grain
   – *allows whisker to grow*
5) Stress gradient drives diffusion to whisker base

M. Sobiech et al 2010:
Stress gradient

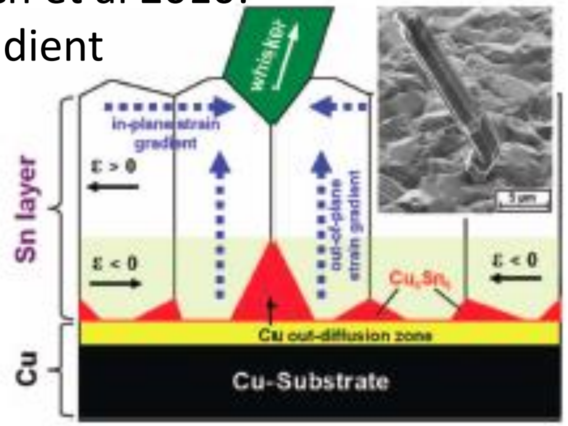
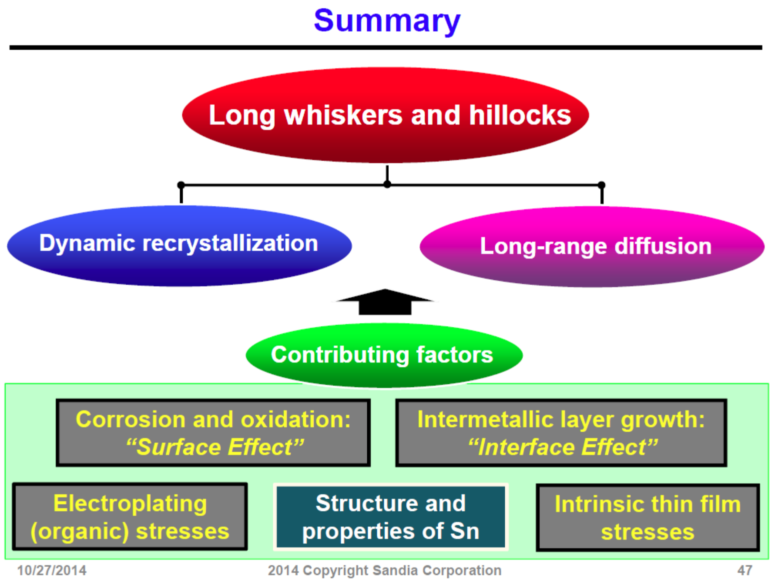
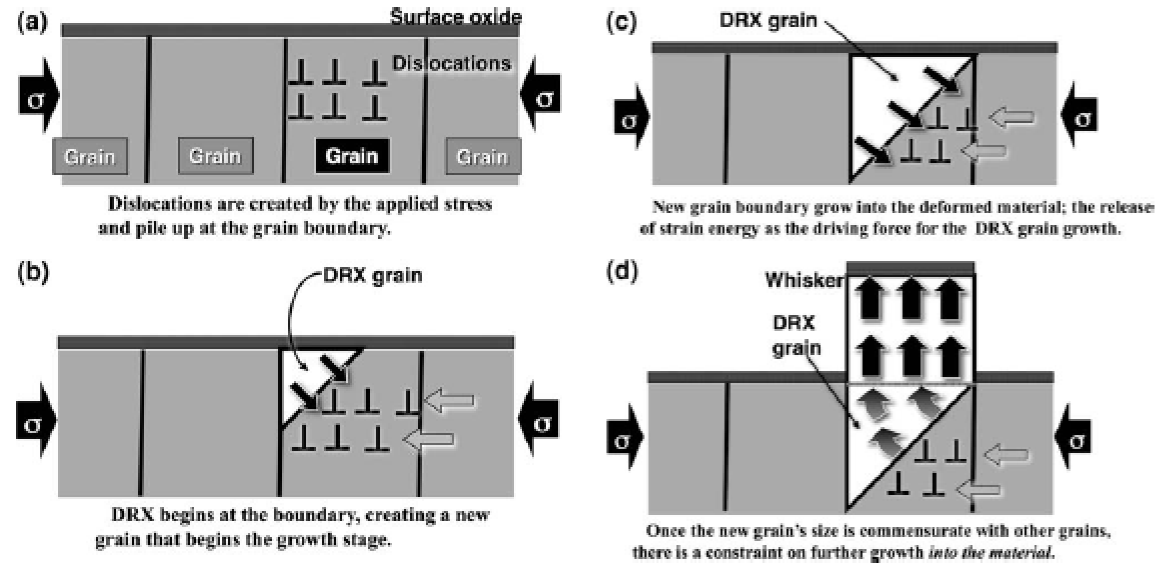


FIG. 1. (Color) Schematic model, on the basis of the results of the present work, of the whisker-formation process in Sn thin films deposited on Cu substrates upon aging at room temperature. The focused ion beam micrograph illustrates the growth morphology of a Sn whisker.

P. Vianco et al 2016: DRX





Some references and summary of models

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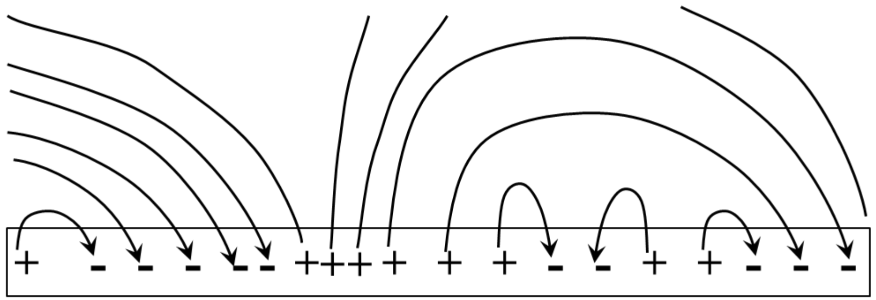
All models discuss some processes in materials and do not discuss why:

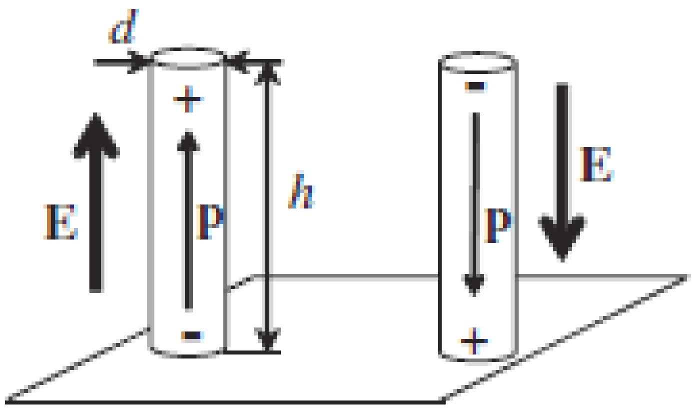
- Whiskers grow long and slim reaching aspect ratios up to 10,000
- They grow on metals
- They are all different and unpredictable
- ... Lots of other problems: concentration, growth rate, statistics...
- No explanation of intermittent growth

Electrostatic theory

Electric forces are omnipresent and long-ranged



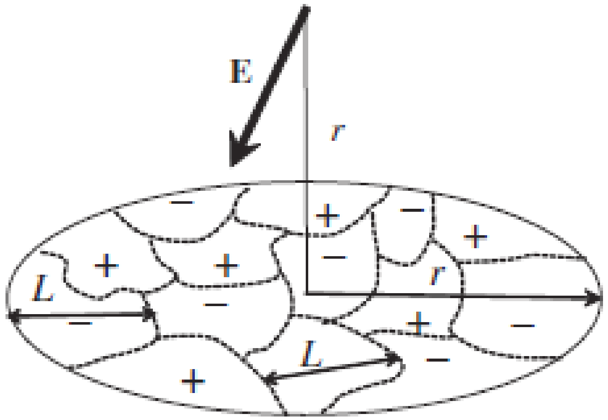
Imperfect metal surfaces contain random charged patches that create significant electric fields, up to 1 MV/cm



Like charges repel producing an outward stress. Where the material is weak enough, whiskers can grow. They provide polarization electrostatic energy gain –**p*E**

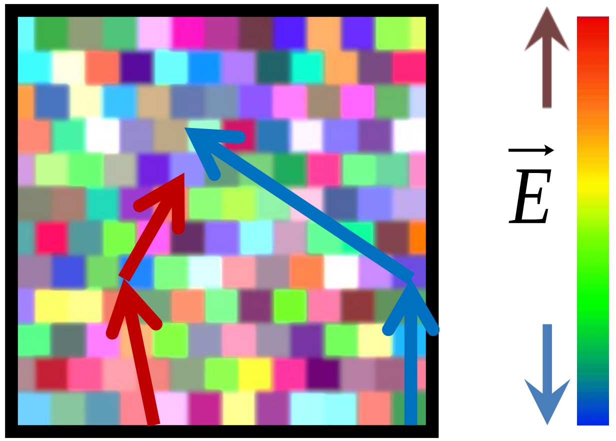
V. G. Karpov, Phys. Rev. Appl.1, 044001 (2014)

Electrostatic forces are random leading to whisker statistics



L is the patch size

Beyond the patch size (*r*>>*L*) whiskers grow in a random field by many oppositely charged patches



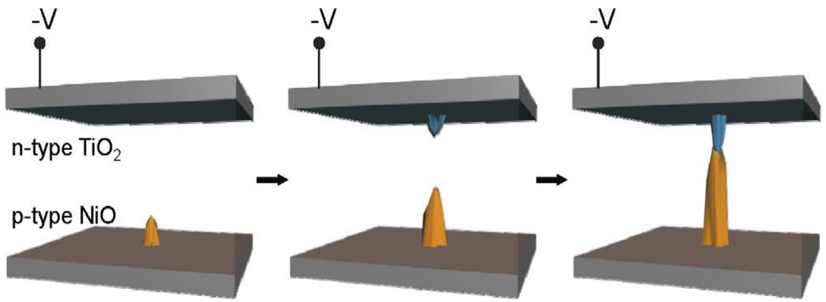
Whiskers along predominantly reddish + or bluish - paths

- Rapid growth while either + or – fields dominate along the length.
- For large lengths, + and – fields start balancing each other.
- Whiskers *stop growing* at certain random lengths (*statistics*)
- Can resume growth after a while

V. G. Karpov, Phys. Rev. Appl.1, 044001 (2014)

Examples of conducting filaments forming in strong electric fields

Many examples of filament formation under electric bias include both detrimental effects (shunting) and useful applications (switching in resistive memory)



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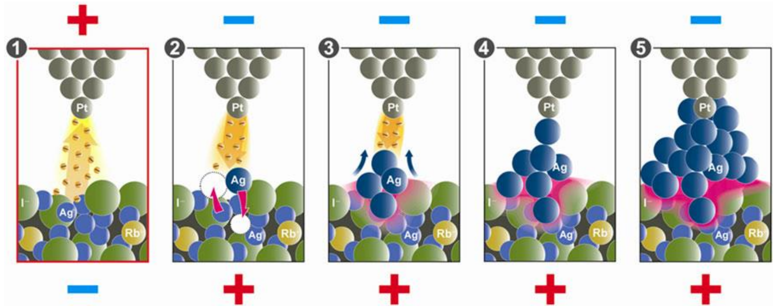

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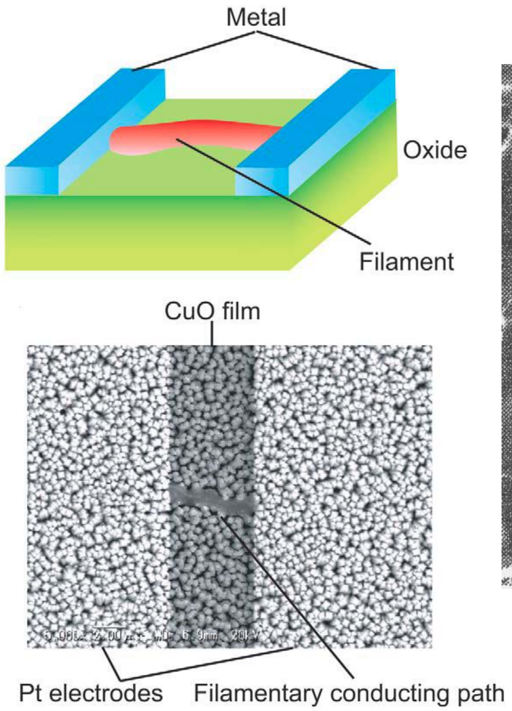
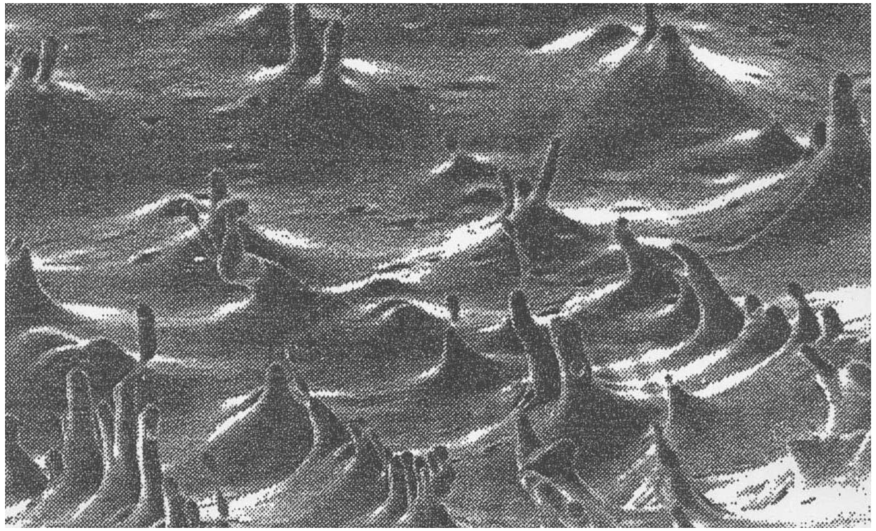


A.Sawa, Materials Today, **11**, 28 (2008)

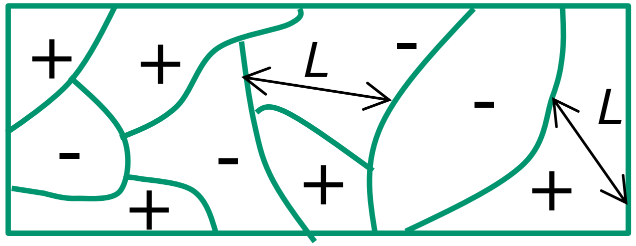


Structures pulled up by a strong electric field on the surface of a molten metal [G. A. Mesyats, Explosive Electron Emission, URO-Press, Ekaterinberg, (1998); p.29].

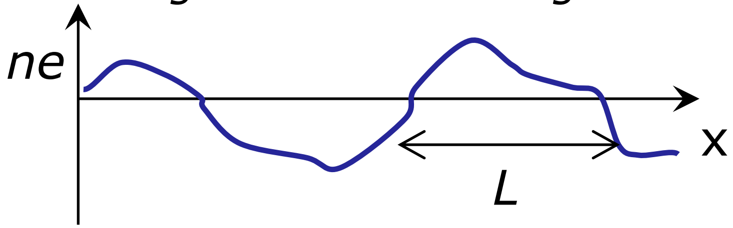
Charge patch model
(older than whiskers)

- The surface must be neutral overall (zero electric flux): hence, combination of positively and negatively charged domains similar to a chess board, but not that ordered.
- Characterized by a single geometrical dimension *L*.

Charge patches top view



Charge variations along a line



REVIEWS OF
MODERN PHYSICS

VOLUME 7 APRIL, 1935 NUMBER 2

Thermionic Electron Emission and Adsorption

Part I. Thermionic Emission*

J. A. BECKER, *Bell Telephone Laboratories*

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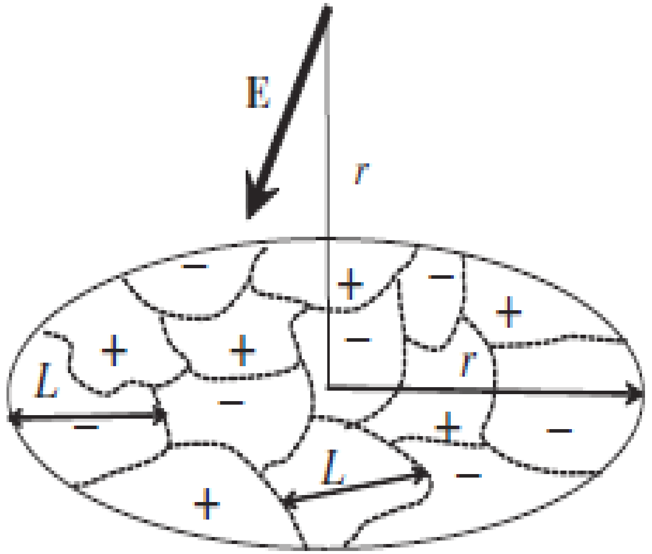
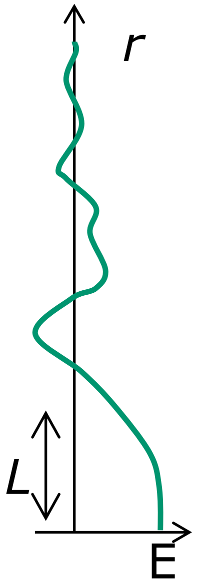
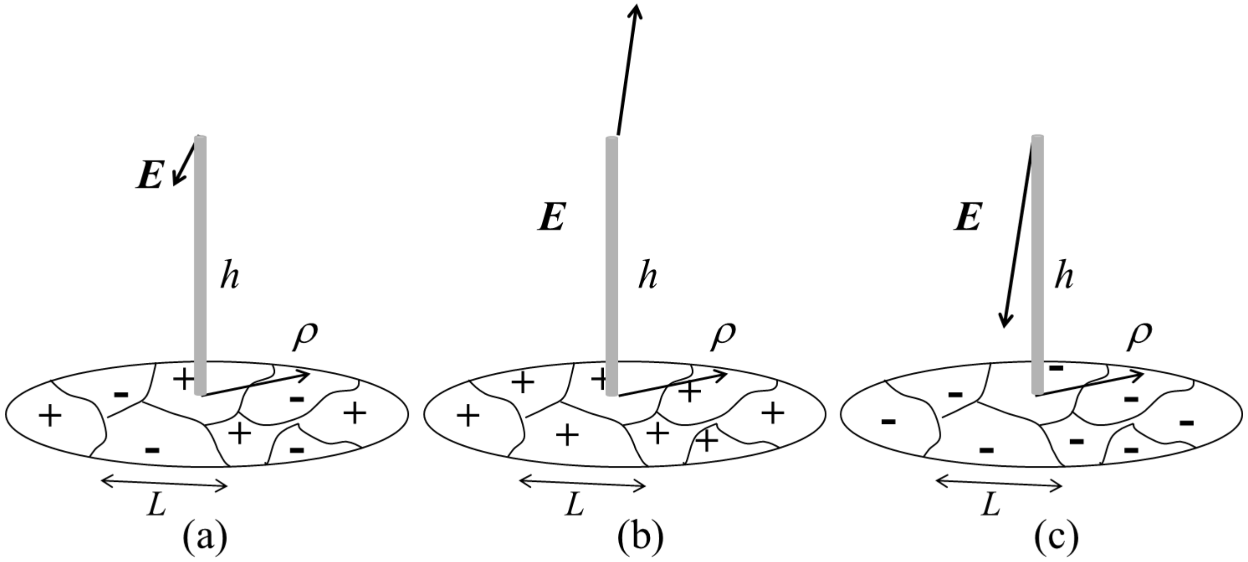
Electric field distribution and energy





In a metal whisker of length h,
the electric dipole moment induced is $p= h^3E$,
the dipole energy gain in the field F_E=$-p*E \sim -h$

On the other hand there is energy loss due to side surface energy $F_S \sim h$

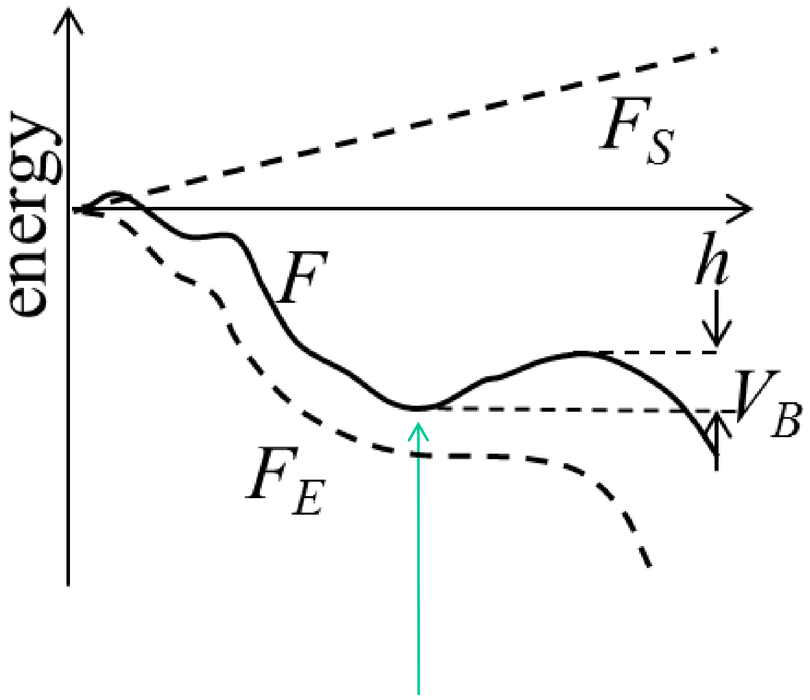


Depending on charge configuration, the fields vary between different regions and so are whiskers.

Some rare configurations [like (b) and (c)]create fields strong enough to make whiskers energetically favorable (F_E+F_S<0)

Whisker statistics: approach

A whisker stops growing when its tip enters a region of low field, so its further polarization gain is overbalanced by the surface energy loss



It stops here, but can resume growth after a while

$$F_E(h) = \frac{-1}{2\left[\ln\left(4h/d\right)-1\right]}\int_0^h \left[\int_0^x E(x)dx\right]^2 dx$$

$$F_E(h) = \frac{-1}{2\Lambda}\int_0^h \xi^2 dx, \quad \xi\left(x\right) \equiv \int_0^x E(x)dx$$

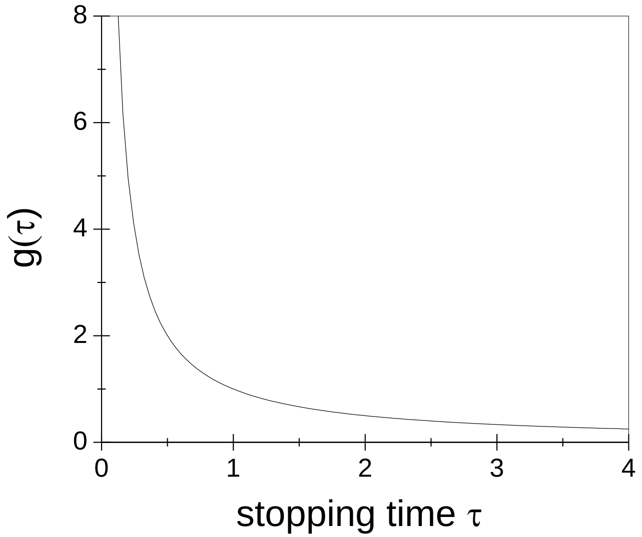
- Via Coulomb's law, ***E*** is a linear functional of surface charge density *n(**r**).*
- Statistics of *n* → statistics of *E* → *statistics of F_E* → statistics of barriers

Whisker statistics: results

Probability densities:

barrier distribution, $\rho(V_B) \approx const$ when $V_B < V_0 \equiv h(neL)^2$

stopping times distribution, $g(\tau) = \dfrac{kT}{V_0}\dfrac{1}{\tau}$



assuming thermally activated $\tau = \tau_0 \exp\left(\dfrac{V_B}{kT}\right)$

h is whisker length, n – surface charge density,
L – patch size, T – temperature, k – Boltzmann's constant

Note that the probability of short stopping times is much larger that that of long times. Short time stoppings can be overlooked

Conclusions

- The electrostatic theory naturally predicts the stochastic intermittent kinetics of whisker growth.
- The stopping barriers probabilistic distribution is close to uniform.
- The stopping time distribution is close to $1/\tau$
- Short time interruptions are more likely and can be overlooked unless intentionally tracked.
- The barriers typically extend over the entire length ranges at which they appear; the next barrier for the same whisker is expected when its length changes by an order of magnitude.
- The characteristic barrier height increases with whisker length linearly and the characteristic stopping time increases exponentially.

Practical suggestion

Industry standards for whisker propensity limited time tests (such as by Joint Electron Devices Engineering Council), need to be approached statistically, predicting with a certain probability the long-term growth, for example, the probability of a certain whisker growth during the desired time interval.

Industrial protocols for such statistical predictions can be attempted based on a theory such as the above quantifying possible losses in the spirit of actuarial analyses.