INSTITUTE FOR RESEARCH IN ELECTRONICS & APPLIED PHYSICS

What do we (and don't we) know about RF breakdown and multipactor?

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Old problems are still attractive

- Both phenomena were identified and started to be analyzed long time ago:

RF breakdown – W. D. Kilpatrick (1953)

Multipactor – P. T. Farnsworth (1934)

Nevertheless, in the last two decades many papers on the theory of these effects have been published.

Why?

What do we know and what don't about them?

RF breakdown

- It is impossible to give an overview of all publications on this topic.
- Instead, we will discuss a few interesting effects and formulate a few questions important for the theory of the RF breakdown

Field enhancement

- It is recognized (not by all researchers) that RF breakdown can be triggered by the field emission.
- Field emission may result from the enhancement of applied fields at microprotrusions.
- It seems possible that on the top of such protrusion one can find another protrusion whose dimensions are much smaller than those of the first one.
- In such tip-on-tip configuration the field enhancement factor is equal to the product of field enhancement factors of each protrusion. (Conjectured but not proven by W. Schottky in 1923)

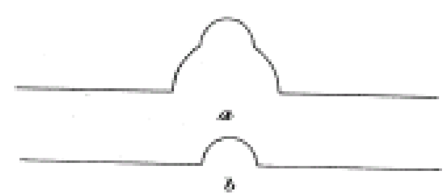


Fig. 6.

des maximalen äußeren Potentialgradienten unmittelbar an der Oberfläche des Leiters eingeht, und daß man bei Flächen, die keine sichtbaren Unebenheiten aufweisen, ungefähr damit wird rechnen können, daß die wahre Feldstärke an den exponiertesten Punkten einer Oberfläche ungefähr eine Zehnerpotenz größer ist als die aus der makroskopisch (d. h. eigentlich schon mit dem Mikroskop) untersuchten Oberflächengestalt folgende.

Field enhancement

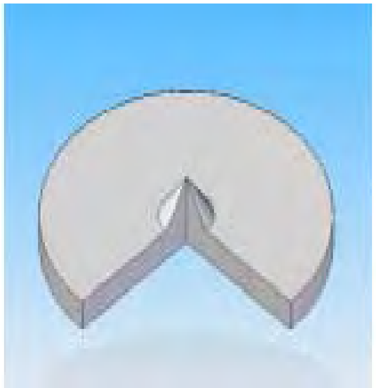
- Q: Should protrusions be visible in SEM (1 nm resolution)?
- A: Not necessarily.

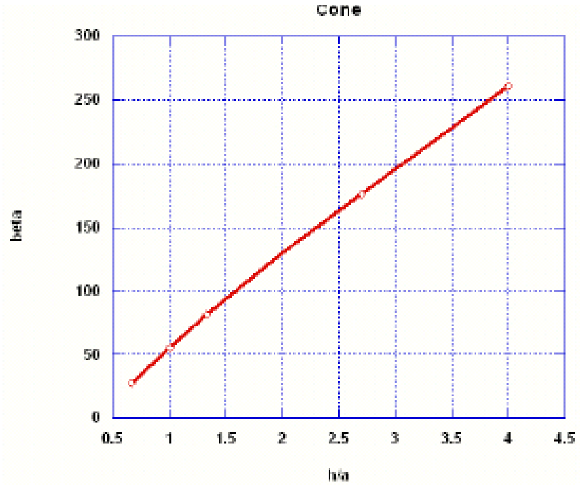
The field enhancement, in line with Laplace equation, does not depend on absolute dimensions:

for a hemisphere it is always =3;

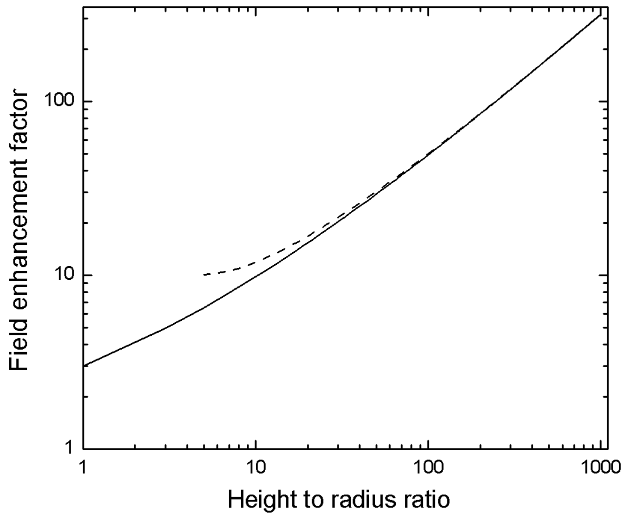
for an ellipsoid it depends on the h/r ratio, but not on absolute numbers.

- Example (after Kosmahl, 1991)





(Courtesy of A. Krasnykh)



Field enhancement

- Once we accept that:

(a) The field enhancement does not depend on absolute dimensions and

(b) The field enhancement in the tip-on-tip configuration is the product of two enhancement factors,

we immediately conclude that field emission should exist **everywhere.**

Q: What is wrong?

A: To cause field emission the field should penetrate into the depth of a few lattice layers to pull electrons out of them.

Example: An ellipsoid made of copper. In copper, each layer has a thickness of 3.6 A. So, the penetration depth should be about 1 nm. When the RF field of 100 MV/m is applied, to have there the potential exceeding the energy barrier of 4-5eV, the ellipsoid should have h/r ratio not smaller than 7.

Field enhancement

Comment: it was shown only this year [Y.Y.Lau et al, APL, 2007] that the field enhancement in the 2D knife-edge tip-on-tip configuration is the product of field enhancement factors of each tip.

Note: Schwarz-Christoffel transformation used there is applicable to 2D configurations only.

One can also find some solutions of Laplace equation near fractal surfaces in the theory of diffusion limited aggregation.

A few questions related to plasma craters

- Origin of plasma craters: molten tips (P. Wilson) or ‘foreign’ molecules (Padamsee and Knobloch)?
- What is the result of tip melting: crater-on-crater configuration increasing the field enhancement (due to superposition of craters’ rims) or smoothening of the surface reducing it?
- When the dark current leads to the tip melting how important is the Nottingham effect?

Molten tips: temporal deformation

- In recent years, there is a strong interest in formation of Taylor cones from molten tips: both static (P. Wilson) and dynamic (S. Calatroni; also Suvorov and Litvinov).
- Reminder: in the RF field, liquid conducting surfaces can oscillate (Fursei et al., 1989)

Suvorov and Litvinov, J. Phys, D, Appl. Phys., Vol. 33 (2000)

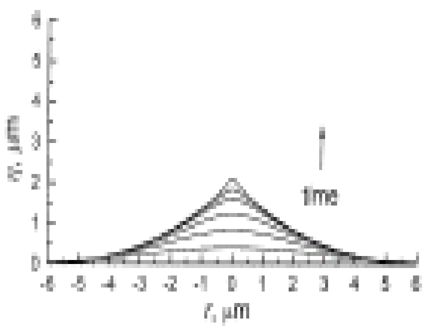
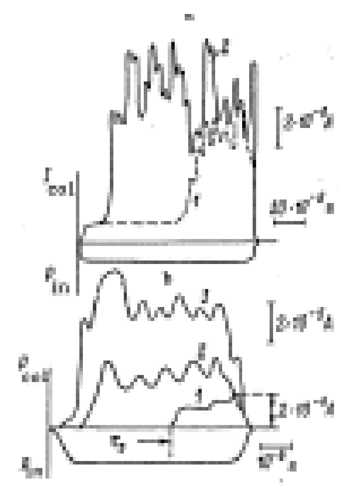


Figure 2. The surface time evolution; initial form is Gaussian with λ = 4 μm, h = λ/10. The surfaces are consecutively represented at time: 0, 0.56, 0.73, 0.81, 0.83 and 0.85 μs.

Kontonistov, Radchenko, Fursei and Shirochin, Sov. Phys. Tech. Phys., Vol. 15 (1989)



RF breakdown

- **To consider the avalanche process leading to RF breakdown it is usually assumed that the process starts from the presence of one free electron in a cubic cm.**
- **In short pulses the probability to have ‘one’ or ‘ten’ electrons is important for time history of the breakdown and its statistics.**
- **Statistical model of microwave breakdown initiation is necessary.**
- **D. Dorozhkyna, V. Semenov et al., “Investigation of time delays in microwave breakdown initiation”, Physics of Plasmas, vol. 13, (2006).**

Reasons for RF breakdown

- Igor Slivkov, “Processes under high voltage in vacuum”, Moscow, 1986:

  Existence of various hypotheses explaining the origin of breakdown should not be interpreted as the absence of our knowledge about this phenomenon, but as the reflection of the fact that there are numerous effects which can lead to breakdown.

Multipactor

- Initially, multipactor was recognized as an avalanche-like growth of the density of free electrons between two metal surfaces where an electron cloud oscillates in synchronism with an RF field. Electron density in this cloud rapidly grows due to the secondary emission multiplication.
- Two-surface and single-surface multipactors
- Metals and dielectrics; RF electric field is either normal (metals) or parallel (dielectrics) to the surface
- Resonant (or single-phase) and non-resonant (multi-phase) multipactors

Multipactor

- Multipactor is important (as a negative effect) for
- microwave transmission lines,
- ceramic output windows in microwave tubes,
- some microwave tubes (such as cross-field devices)
- space-borne communication equipment and
- accelerator applications.

Multipactor

- In different areas, multipactor occurs in different conditions. Therefore corresponding models developed for one case can be not valid for another.
- Studies of multipactor phenomena in cross-field devices and in output windows were sponsored by microwave tube manufacturers (Vaughan, IEEE Trans. Electron Dev., 1988; Riyopoulos, Chernin and Dialetis, Phys. Plasmas, 1995)
- At present, studies of output windows are in the focus of the MURI sponsored by AFOSR (MURI-04).
- Recognition of the importance of this problem for a given application should lead to the support of its studies.

Multipactor

- It looks like the multipactor is not a serious obstacle for metallic accelerating structures, but can be important for dielectric-loaded structures.
- The first theory of multipactor in such structures was developed by John Power and co-workers (J. Power et al., PRL, 2004).
- Present activity – this morning.