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Phenomenological description of vacuum breakdown

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\textbf{1. Potential mechanisms of vacuum breakdown. }The field electron emission (FE), where electrons are released from cold negative electrodes due to the applied electric field, is a necessary step in the development of vacuum breakdown. It is well known that the field emission current from cold electrodes in vacuum exceeds, by orders of magnitude, values given by the quantum mechanical Fowler-Nordheim formula, evaluated in terms of the applied electric field (which in the simplest case of a parallel-plate gap equals V/d, where V is the interelectrode voltage and d is the gap width). Various mechanisms for this enhancement of electron emission have been postulated.

The most popular mechanism is the amplification of the applied electric field by microprotrusions, pre-existing on the surface of the negative electrode or resulting from the application of the electric field. The conventional problem with this hypothesis, as far as pre-existing microprotrusions are concerned, is that in order to explain values of the field emission current observed in the experiment, the microprotrusions have to be assumed to be quite slender (needle-like), and such protrusions are not normally seen on electrode surfaces; e.g., section 3.1 of \cite{Latham1991} and \cite{Descoeudres2009b,Zadin2014}. Still, this point is far from having been clarified; for example, analysis of deviations from the gas discharge similarity law, observed at high and very high pressures in experiments on discharge ignition and breakdown in corona-like configurations, appears to confirm the existence of the microprotrusions on the surface of the electrodes \cite{2021b}.

Another popular mechanism is a local reduction of the work function of the cathode material, caused by, e.g., lattice defects or adsorbed atoms. However, this effect seems to be insufficient to explain the observed values of the field emission current; e.g., \cite{Sinelnikov2014,Wuensch2019}. Other interesting hypotheses proposed in the literature include 'nonmetallic' electron emission mechanism \cite{Latham1991}, enhancement of field emission by waves confined to the metal surface (plasmons) \cite{Wuensch2019}, and mobile dislocations near the surface of electrodes \cite{Engelberg2020}. Thus, there is still no widely accepted understanding of the mechanism of enhancement of field electron emission from cold electrodes in vacuum, in spite of several decades of active research.

What other mechanisms may play a role at the initial vacuum stage of breakdown, apart from field emission, if any? The most popular mechanism is fast heating of cathode protrusions due to shape-related runaway process; works \cite{Kyritsakis2018, Veske2020, Barengolts2019a, Barengolts2019b, Mofakhami2019,2021k} may be mentioned as recent examples. Other mechanisms mentioned in the literature (e.g., \cite{Descoeudres2009b}) include gas desorption at the anode caused by an intense FE current, melting of a spot at the anode by a heavy bombardment of FE electrons, macroparticles that are released from the electrodes by field induced stresses and subsequently partly evaporated by the FE current, direct field evaporation of surface atoms. The critical transition in the density of the mobile dislocations within a metal was proposed as a vacuum breakdown mechanism in \cite{Engelberg2018,Engelberg2019}.

Other mechanisms come into play as the breakdown develops, in particular, a transition from the field to thermo-field to thermionic emission, vaporization of the electrode material, production of plasma by ionization of the metal vapor, melting of the electrode material, and formation of a crater on the electrode surface with eventual droplet detachment.

\textbf{2. Difficulties in numerical modelling. }The initial stage of breakdown in high-electric field has been simulated in a number of works (e.g., \cite{Kyritsakis2018, Veske2020, Barengolts2019a, Barengolts2019b, Mofakhami2019,2021k}), however it appears that the whole process, including the formation of craters, has not been simulated in a self-consistent manner up to now. This is in contrast with the cases of spot ignition in low-voltage vacuum arcs and unipolar arcs in fusion devices, where several works dedicated to the modelling of the whole life clycle of a spot have been published; e.g., \cite{2019d} and references therein. Apart from the uncertainty and diversity of the dominating physical mechanisms, the main difficulty lies in the presence of very different length scales. For example, microprotrusions simulated in \cite{Kyritsakis2018} have the tip radius of $3\mathrm{nm}$ and a total height of $93.1\mathrm{nm}$, while the crater radius is typically a few micrometers or bigger.

\textbf{3. Phenomenological approach. }A phenomenological description of the field electron emission is used in practice: experimental current-voltage characteristics of field emission from cold electrodes in vacuum are fitted by the Fowler-Nordheim formula with the applied electric field being multiplied by the so-called field enhancement factor β, which has to be of the order of 10^2 or higher; e.g., reviews \cite{Latham1991,Latham1995,Wuensch2019} and references therein.

A correlation of the vacuum breakdown field with the field enhancement factor β, determined by means of analysis of the measured field emission currents, was reported in \cite{Descoeudres2009b}. It was found that the product βE_b, where E_b designates the applied DC breakdown field (and hence the product βE_b may be interpreted as an "effective" average microscopic local breakdown field inside the emission center), is a constant value only dependent on the material and not on β or the gap spacing. The value of βE_b around 1.1×10^{10} \textrm{V/m }$\mathrm{V/m}$ was found for copper electrodes.

The existence of this correlation makes it natural to explore the possibility to describe the initial stage of vacuum breakdown within the framework of the same phenomenological approach, i.e., in terms of the field enhancement factor β without invoking any special mechanism for the breakdown apart from the mechanism responsible for the enhancement of field emission. Such an attempt is described in this contribution. A half-space filled with a metal is considered. A surface-directed electric field E_w exists at the half-space surface. The temperature distribution inside the half-space is uniform at $300\mathrm{K}$ at the initial moment and evolves with time under the action of electron emission heating (the Nottingham effect) or cooling at the surface and the Joule heating inside the metal. The evolution of the temperature distribution is simulated by solving the heat conduction and current continuity differential equations in the half-space. The thermal and electrical conductivities of the half-space material are given functions of the local temperature; the dependencies for copper are employed. The electron emission current density at each point of the surface, which serves as a boundary condition for the current continuity equation, is evaluated by means of the Murphy-Good formalism in terms of the local value of the surface temperature and of the electric field equal to βE_w. The heat flux from the surface inside the metal is evaluated with account of electron emission heating or cooling; the boundary condition for the thermal conduction equation.

In the framework of this model, the parameter governing the temperature evolution inside the metal is the product βE_w, rather than β and/or E_w separately, in agreement with the above-mentioned experimental findings \cite{Descoeudres2009b}. Two cases have been considered: β is the same at each point of the surface, and β varies along the surface. In the first case, the solution is 1D: heat propagation inside the metal is the same at each point of the surface. If βE_w is high enough, there is a very fast increase of the temperature and the current density at, or very near, the surface: the maximum temperature reaches the critical temperature of copper (8390K) within approximately 2ns for $\beta E_w = 10^{10}\mathrm{V/m}$ (and within 1 microsecond for $\beta E_w = 0.7 \times 10^{10}\mathrm{V/m}$, while there is virtually no heating on the microsecond time scale for βE_w below $0.5 \times 10^{10}\mathrm{V/m}$). At such applied electric field values, the Joule heating underneath the surface comes into play and overtakes the Nottingham effect. This is a manifestation of the so-called thermal runaway. This instability has been extensively studied in the context of low-voltage vacuum arcs (e.g., review \cite{Hantzsche2003}); its shape-related version was studied in the context of high-voltage vacuum breakdown initiated by microprotrusions (e.g., \cite{Kyritsakis2018, Veske2020, Barengolts2019a, Barengolts2019b, Mofakhami2019,2021k}).

Also considered in the modelling was the axially symmetric case where β varied along the surface as a Gaussian function of the distance from the origin with the height of the curve's peak of 150 and the standard deviation of 40nm. (Note that the latter value was chosen in accordance with the measurements \cite{Descoeudres2009b}, which gave the diameter of the emitting area typically between 20 to 80nm). For $E_w = 10^8\mathrm{V/m}$, the critical temperature was reached within 8ns.

\textbf{4. Conclusions. }It appears to be possible to describe the initial stage of high-voltage vacuum breakdown within the framework of the phenomenological approach, i.e., in terms of the field enhancement factor without invoking any special mechanism for the breakdown apart from the mechanism responsible for the enhancement of field emission. It is of interest to exploit this option in the modelling of advanced stages of vacuum breakdown, which would take into account a transition from the field to thermo-field to thermionic emission, vaporization of the cathode material, production of plasma by ionization of the metal vapor, melting, and formation of a crater with eventual droplet detachment, on the level comparable to that reached in the modelling of the whole life-cycle of spots in low-voltage vacuum arcs and unipolar arcs in fusion devices (\cite{2019d} and references therein).

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Topic

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