Stories From China

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Direct Observation of Electric Field–Induced Surface Modifications: A First Step to Unravel the Origin of Vacuum Breakdown

The vacuum breakdown issue severely hinders the performance of vacuum electrical devices, such as vacuum interrupters, X-ray sources, fusion reactors, and particle accelerators [1]–[3]. In general, vacuum breakdown is initiated by thermal instability at the cathode or anode due to the electron emission current, which heats the protrusion itself or transfers kinetic energy to the anode. Then, the initial vapor and ion population could be produced by the atom evaporation due to extreme heating, induced by the field electron emission current. Due to the evaporated atoms, the gap pressure increases and the mean free path of electrons may become less than the gap distance, where avalanche ionization will occur and cause the plasma discharge. Thus, the dynamics of electron emission and the electrode's properties will determine the dielectric strength and insulation performance of the gap.

Therefore, nano-protrusion (NP) on a metal surface and its inevitable contamination layer under a high electric field is often considered as the primary precursor that leads to vacuum breakdown. Previous research has suggested that these breakdown precursors might spontaneously form on a metal surface under a high electric field [4]–[6]. In a recent Featured Review Article [4], Guodong Meng and Lay Kee Ang et al. successfully matched the emission physics to the physical modification of the surface under the intense electric fields for the first time (Figure 1). For such a process to occur, an extremely high geometric field enhancement (of the order of several hundreds) by localized sharp protrusions on the metal surface needs to be assumed. It has not been observed experimentally for the metal surface after prior conditioning.

Recently, Guodong Meng and Andreas Kyritsakis et al. reported a direct real-time observation of the growth of a nano-protrusion on a carbon-coated tungsten nanotip for the first time by in situ transmission electron microscope (TEM) imaging, trying to discover the complicated interaction between high electric fields and materials at the atomic scale. In this work, the accompanying enhanced field emission behavior, which could initiate vacuum breakdown, was simultaneously recorded. They found that under certain conditions, the FE current-voltage (*I-V*) curves switched abruptly into an enhanced-current state, implying the growth of an NP, which was perfectly consistent with the results of field emission simulations that a NP has grown at the apex of the tip (Figure 2). This hypothesis was also confirmed by the repeatable in situ observation of such a nano-protrusion and its continued growth during successive FE measurements in TEM. They attributed the nano-protrusion growth to field-induced biased surface diffusion, after excluding the possibility of field-induced plastic deformation by FEM simulations. The research article has been published in *Physical Review Letters* [5].

These findings provide a plausible explanatory mechanism for the appearance of field-enhancing features necessary to initiate electrical breakdown in vacuum, forming an excellent starting point to solve this long-standing and critical problem in the vacuum breakdown research community. In addition, it is worth noting that much recent research has seen the considerable discrepancies between classical predictions and experimental observations in systems with deeply nanoscale feature sizes, which are typically evident below about 10 to 20 nanometers [6]. Therefore, this proposed in situ experimental technique at atomic scale could be of great interest for better understanding the nanoscale physics, which is believed to surely "roll up" to a variety of applications from chips to accelerators.

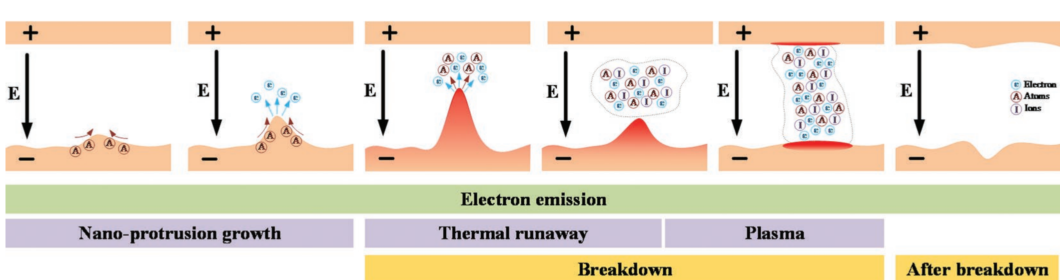

Figure 1. An illustration of the breakdown process at nanoscale [1].

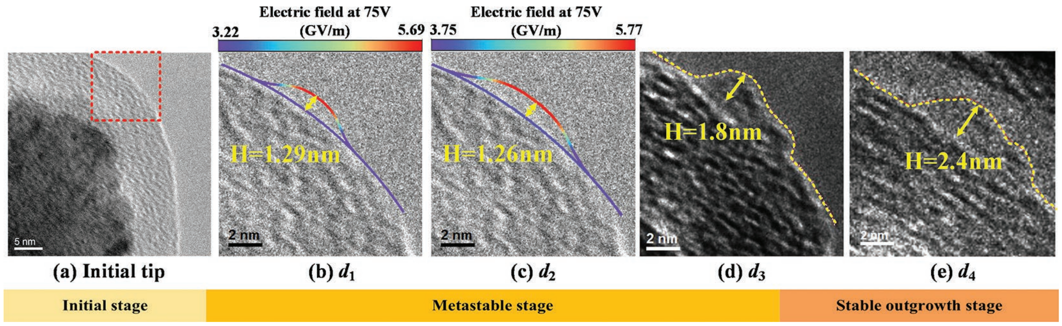

Figure 2. Schematic diagram of field-induced nano-protrusion growth.

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References

[1] G. Blaise and C. Le Gressus, "Charge trapping-detrapping processes and related breakdown phenomena," in *High Voltage Vacuum Insulation: Basic Concepts and Technological Practice*, R. V. Latham, Ed. San Diego, CA: Academic Press, 1995.

[2] G. McCracken, "A review of the experimental evidence for arcing and sputtering in tokamaks," *J. Nucl. Mater.*, vol. 93-94, pp. 3–16, 1980.

[3] P. N. Burrows, N. C. Lasheras, L. Linssen, M. Petrič, A. Robson, D. Schulte, E. Sicking, and S. Stapnes, Ed. *The Compact Linear Collider (CLIC)—2018 Summary Report*. CERN (European Organization for Nuclear Research), 2018, doi: 10.23731/CYRM-2018-002.

[4] Y. Li, L. Ang, B. Xiao, F. Djurabekova, Y. Cheng, and G. Meng, "Review of electron emission and electrical breakdown in nanogaps," *Phys. Plasmas*, vol. 31, no. 4, article 040502, 2024.

[5] G. Meng, Y. Li, R. A. Koitermaa, V. Zadin, Y. Cheng, and A. Kyritsakis, "*In situ* observation of field-induced nanoprotrusion growth on a carbon-coated tungsten nanotip," *Phys. Rev. Lett.* vol. 132, article 176201, 2024.

[6] Y. Yang, D. Zhu, W. Yan, A. Agarwal, M. Zheng, J. D. Joannopoulos, P. Lalanne, T. Christensen, K. K. Berggren, and M. Soljačić, "A general theoretical and experimental framework for nanoscale electromagnetism," *Nature*, vol. 576, pp. 248–252, 2019.