Cryogenic Field Emission Enhancement in Vertically Aligned Carbon Nanotubes Cold Cathodes through Tip Morphology Engineering

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Vertically aligned carbon nanotubes (VACNTs) represent a promising solution as cold electron cathode, due to their high aspect ratio and nanoscale tip radius. Their field emission (FE) properties enable low turn-on fields and stable current densities, from fA to mA regime [1]. Moreover, they present a superior mechanical, electrical and chemical stability in ultra-high vacuum, both at room and cryogenic temperature [1]. These qualities make VACNT-based cathodes highly attractive as scalable, microstructured electron sources, enabling robust integration into compact, chip-level devices for fundamental physics applications, including compact accelerators [2], precision electron injectors [3], and low-background detection systems in rare-event dark matter experiments [4].

We present a quantitative investigation of the correlation between tip morphology and FE properties of VACNTs at cryogenic temperature. Three VACNT samples were systematically characterized to assess the impact of tip morphological modifications on electron emission performance. Field emission measurements were conducted at $T = 2.8$ K, enabling operation close to the ideal conditions of the Fowler–Nordheim model and representing one of the first observations of FE in vacuum below 10 K [5] .

The field enhancement factor β was extracted through Fowler–Nordheim analysis, supported by independent and precise determination of the work function via ultraviolet photoemission spectroscopy (UPS) and accurate evaluation of the cathode–anode distance. Plasma etching was found to significantly enhance emission performance, yielding β values up to $(15.2 \pm 2.5) \times 10^3$, more than doubling that of the as-grown sample .
A detailed morphological analysis was carried out using atomic force microscopy, enabling statistical evaluation of the tip radius of curvature r_c. By correlating morphological and electrical data, we establish a clear inverse relationship between the field enhancement factor and the tip curvature radius, described by $\beta(r_c) = k/r_c$, with $k = (175 \pm 13)$ µm.

This result provides a predictive framework for estimating FE performance directly from surface morphology measurements, bypassing the need for complex cryogenic setups.

References

1. Abraham, J., Thomas, S., Kalarikkal, N., *Handbook of Carbon Nanotubes*, Eds.; Springer International Publishing: Cham, 2022.
2. Tang, X. et al. Vertically Aligned Carbon Nanotube Microbundle Arrays for Field-Emission Applications. ACS Appl. Nano Mater. 3, 7659–7667 (2020).
3. Mihalcea, D. et al. Ampère-Class Pulsed Field Emission from Carbon-Nanotube Cathodes in a Radiofrequency Resonator. Applied Physics Letters 107, 033502 (2015).
4. Pandolfi, F. et al. The dark-PMT: a novel directional light Dark Matter detector based on vertically-aligned carbon nanotubes. J. Phys.: Conf. Ser. 2156, 012051 (2021).
5. Cecchini, L. et al. Quantitative correlation between carbon nanotube tip morphology and field emission properties at cryogenic temperature. Nanoscale 17, 21260–21267 (2025).