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A PLATFORM TO OPTIMIZE THE FIELD EMISSION PROPERTIES OF CARBON-NANOTUBE-BASED FIBERS (POSTPRINT)

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14. ABSTRACT *(Maximum 200 words)*

Building on recent efforts [1-4] to characterize carbon nanotube fibers (CNFs) and electron emission [5,6] suitable for compact, high power, high frequency, vacuum electronic devices, this paper describes a proposed exhaustive approach towards optimizing CNF field emission (FE) properties. It outlines how a platform geared towards meaningful comparisons between different CNF-based emitters can be developed. The platform envisages an iterative procedure involving (a) the growth, processing, and functionalization of CNFs, (b) full investigation of the CNF material properties before and after FE diagnosis, and (c) multi-scale modeling of FE properties, including self-heating, shielding effects and beam characteristics in the CNFs and in the emitting carbon nanotubes (CNTs) at the fiber apexes. The modeling would be applicable to a wide variety of CNFs and wire-like sources, and would provide essential feedback to the growth, processing, and functionalization of CNFs, in order to optimize their FE properties (especially long-term stability, low noise, and maximum emission current, current density and brightness.

15. SUBJECT TERMS
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A platform to optimize the field emission properties of carbon-nanotube-based fibers

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Abstract—**Building on recent efforts [1-4] to characterize carbon nanotube fibers (CNFs) and electron emission [5,6] suitable for compact, high power, high frequency, vacuum electronic devices, this paper describes a proposed exhaustive approach towards optimizing CNF field emission (FE) properties. It outlines how a platform geared towards meaningful comparisons between different CNF-based emitters can be developed. The platform envisages an iterative procedure involving (a) the growth, processing, and functionalization of CNFs, (b) full investigation of the CNF material properties *before and after* FE diagnosis, and (c) multi-scale modeling of FE properties, including self-heating, shielding effects and beam characteristics in the CNFs and in the emitting carbon nanotubes (CNTs) at the fiber apexes. The modeling would be applicable to a wide variety of CNFs and wire-like sources, and would provide essential feedback to the growth, processing, and functionalization of CNFs, in order to optimize their FE properties (especially long-term stability, low noise, and maximum emission current, current density and brightness.**

Keywords—carbon nanotube fibers; field electron emission; self-heating effects; multiscale modeling; Nottingham effect

I. Introduction

CNTs have proven to be excellent field electron emitters due to their high aspect ratio and high electrical and thermal conductivity. For over a decade, research has focused on using CNTs to fabricate free standing films, yarns, and—more recently—CNFs. The aim is to transfer their exceptional physical properties from the nanoscale to the macroscale. A problem in comparing field electron emission results from different groups is that quite varied methods are used for (a) CNT synthesis (intrinsic structural and chemical properties of the individual tubes, diameter and length distribution, percentage of single versus multiple wall CNTs), (b) purification (closed or open end CNTs, presence of impurities), (c) cathode morphology (CNT/CNF alignment, spacing between emitters), and (d) FE measurement and characterization of key metrics, such as effective field enhancement factor and emission area. It is imperative to address issues relating to whether observed variations in the FE properties of different cathodes are due to different intrinsic properties of the CNTs, different preparation methods, differences in FE measurement arrangements, or how "effective" parameters arise from the statistics of their underlying causes. As part of this, issues relating to the standardization of how basic theory is presented, to standardization of data-analysis methods, and to how macro features affect micro performance, need to be addressed.

II. The Platform

The FE characteristics of a CNF cold cathode depend on the morphology, chemical and thermal stability, mechanical properties, adsorption kinetics characteristics, emission site density, electrical conductivity, and work function of the cathode materials, and also on the measurement conditions (background pressure in vacuum chamber, cathode temperature, and distance between cathode and anode). All these should have an influence on the size of irreversibility loops observed in the FE data. Therefore, understanding the inherent physical processes and mechanisms involved in FE from CNFs is necessary, as it will open an avenue for controlling the emission properties and fabrication of CNF cold cathodes. This is an extremely important issue since irreversible behavior should be totally nonexistent or at least reduced to a minimum for practical applications. A thorough characterization of a practical CNF based cold cathode should answer the following fundamental questions.

1. Density of field emitters: How many CNTs and/or CNFs participate in FE? What is the contribution to FE from the sidewall and tip of the fiber? What is the spatial distribution of the field emitters? How does the number of field emitters vary with the applied bias?

2. FE mechanisms: When does Fowler-Nordheim tunneling prevail and over what range of bias? How important are the effects of Coulomb repulsion between adjacent emitting CNTs on the FE characteristics? When do space-charge effects become important and affect the FE properties of the fiber?

3. Fiber conditioning: The conditioning process should address the following questions. What is the importance of the conditioning procedure on the maximum emitted current? What is the influence of the maximum applied voltage on the size of the irreversibility loops? What are the different mechanisms affecting the conditioning of a fiber?

4. Irreversible behaviour: what are the various mechanisms responsible for the irreversibility loops observed in the FE data? How are the irreversibility loops related to the conditioning history of the fiber?

5. Outgassing issues: What are the species (both neutral and ionized) desorbed from the fiber during FE? What are the outgassing properties of the cathode and anode? How do they correlate? What are the mechanisms of desorption?

6. Self-heating effects: What are the mechanisms contributing to self-heating effects in the fibers? What is the power dissipation in the anode? How does radiation loss compare to power dissipation in the fiber? What is the temperature distribution along the fiber? How does this affect FE from the fiber sidewall and its tip?

7. Anode characterization: What are the mechanisms that lead to the presence of carbon on the anode after FE experiments? What is the contribution from thermal evaporation from cathode? How are the effects of secondary emission from the anode affecting the FE measurements?

8. Energy distributions: What are the energy distributions of the ionized and neutral gaseous species formed as a result of desorption during FE? What is the correlation between the desorbed species and the collected electrons at the anode?

9. Noise issues: What is the correlation between the noise in the electron emission current and the noise in the flux of collected gas species resulting from desorption during FE?

10. Emission stability test: How are the short-term stability (low-frequency current fluctuations) and the long-term stability (e.g., over tens of hours) affected by the cathode and anode changes in morphology and composition?

11. Photon emission: What are the sources of photon emission from an operating cathode? What are the importance of Joule heating, Nottingham/Henderson effects, ion bombardment, and plasma formation in front of the fiber surface? How is the energy spectrum of emitted photons correlated to the self-heating effects in the fiber? How does it vary with applied bias and cathode-to-anode separation?

12. Emitter failure: What are the mechanisms leading to the eventual destruction of the fiber? What is the relevance of self-heating effects?

The issues listed are highly correlated, but only a few are typically considered at a time in the growing number of reports on the FE of new CNT based cold cathodes. In this paper, we will describe a comprehensive platform to provide systematic answers to the issues listed above. The platform consists of an iterative procedure between the growth, processing, and functionalization of CNFs, a full investigation of the CNF material before and after FE diagnosis including appropriate CNF conditioning, and a modeling effort to provide the essential feedback to the growth, processing, and functionalization of the fibers in order to optimize their FE properties.

III. Applications

The proposed platform should pave the way towards the development of reliable CNF field emitters, with potential applications as high-power vacuum electronic devices in areas spanning communications, radar, and space applications. This program is motivated by the urgent need for advanced cold cathode electron emitters for compact, high power, and high frequency vacuum electronic devices. Towards that goal, new cold cathode concepts are needed to provide emitters that must operate at temperatures less than 1000 °C, provide total emission current of at least 10 mA at a current density of at least 1 A/cm^2, and be capable of at least one hour of CW operation.

CNFs should also find applications in flat panel displays, electron beam lithography and microscopy, advanced accelerators, free electron lasers, x-ray generation, x-ray miniature systems, high power microwave generation, and ion propulsion systems.

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