FIELD EMISSION MICROSCOPY OF CARBON NANOTUBE FIBERS

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ABSTRACT

Large-area field emission cathodes made from carbon nanotube (CNT) fiber have long been promising as the next generation electron sources for high-power radio frequency (rf) or microwave vacuum electronic devices (VEDs). CNTs have excellent field emission properties such as low turn-on voltage and high output current at electric fields as low as ~10 MV/m, as compared to the legacy metal emitter technology. Therefore, CNT technology has the potential to decrease the operating voltage and simplify VED systems. However, in addition to high beam charge, beam-driven radiation sources require electron beams with low emittance (i.e. high brightness), which must be provided in a stable continuous fashion. Although there have been many studies on CNT fibers’ emission current performance, there is not sufficient research on their emission uniformity, emittance, brightness, and overall upper performance limitations specific to the CNT material itself. The lack of these important characterization metrics led to the work presented in this thesis. Not only were the conventional current-voltage (I-V) relations measured and evaluated, but also the electron beams carrying the currents were monitored in situ in real-time by projecting the beam onto a scintillator screen in a custom field emission microscope. These enabled the measurement and evaluation of emittance and brightness. The existing bottlenecks limiting the fiber’s performance were uncovered for the first time and new advanced CNT fiber cathode designs were proposed and engineered accordingly.

In Chapter 2, various standard (previously attempted) designs of CNT fiber cathodes were tested in the field emission microscope. The results showed that all cathodes had high emittance, low brightness, a large beam spread, non-uniform emission, current saturation, and instability. Hot spots and microbreakdowns were observed during emission. Analysis of the data revealed that all these problems were due to the formation of stray emitters on the cathode surface during emission. It was concluded that the tested fibers failed to provide any reasonable beam quality regardless of the cathode geometry.

Exceptionally non-uniform current emission observed in the experiments raised the question about the mechanism of current saturation when the output charge failed to keep up with the increasing electric field. In Chapter 3, a computational method was developed to extract the emission area from the emission micrographs and then calculate the emission current density. It was found that the current density saturated
quickly and stopped obeying the Fowler-Nordheim law. It was demonstrated that the saturation effect occurred because the local current density reached a maximum level limited by the number of carriers and their finite transit time inside the bulk material's depletion region. It was concluded that overcoming the saturation issue is only possible if uniform emission can be achieved.

In Chapter 4, a brand new and unique cathode design was developed that successfully solved all the problems caused by stray emitters. It was demonstrated that the new design provided a uniform and stable electron beam with a small divergence angle, resulting in a beam with low emittance and high brightness. This result is a significant advancement that outlines a feasible path toward utilizing CNT fiber electron sources for practical VED applications. More specifically, it was observed that the entire cathode surface of a radius of approximately 75 μm emitted uniformly (with no hot spots) in the direction of the applied electric field. From this, the normalized dc current brightness was estimated as $B_N = 3.7 \times 10^{10} \text{ A/m}^2\text{rad}^2$ using the estimated emittance of 52 nm rad. From this, the brightness in the pulsed mode, the preferable mode in most VED HPM applications, was predicted to attain a notable value of $B_N = 4.4 \times 10^{15} \text{ A/m}^2\text{rad}^2$.

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