

Individual Carbon Nanotube Cold Field Emitters: Experimental and Modeling Studies of Integrated System Architecture

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ABSTRACT

We report a fabrication technique for producing cathode structures comprising of an individual multi-walled carbon nanotube (MWNT) emitter. Two cathode structures are fabricated based on 1) an etched Ni wire and 2) a Si microstructure onto which a MWNT is attached. These two cathode structures exhibit reproducible current-voltage curves, however, each cathode demonstrates very a different turn-on field. We employ Technology Computer Aided Design to model the experimental structures. Based on electrostatic simulations, we obtain macroscopic turn-on fields that are within 0.2 V/ μm of the values determined experimentally. We also investigate the effect of cathode area on the field emission characteristics of individual nanoscale cold field emitter. Our results reveal that the area of support cathode structure can more than double the magnitude of the required turn-on voltage and thus must be considered when integrating nanotube emitter into macroscale systems and devices.

Keywords: carbon nanotubes, cold field emitters, nanostructure system architecture, computer aided design

1 INTRODUCTION

Individual carbon nanotube (CNT) cold field emitters are attractive as point electron sources because of their low energy spread, high brightness, and low power consumption [1-3]. Potential applications for such electron sources as a part of an integrated system include advanced miniaturized electron microscopy and portable X-ray tubes. Precision fabrication and integration of nanoscale structures to macroscale systems has been a major challenge to realizing nanotechnology.

In this paper, we present a novel fabrication technique for individual carbon nanotube based field emission cathodes. Our experimental results are complemented by the development of a simulation technique employed in this work to investigate the field emission characteristics of these individual CNT cathodes. We present results

quantitatively showing the effect of the area of support cathode structure on the turn-on voltage, which will prove useful for integrating the emitter into an electron beam system.

2 EXPERIMENT

Low-density Multi-Walled CNTs (MWNTs) are grown on a metal wire by the CVD method [4]. Individual CNTs are selected and attached to their respective support structures using an inverted optical microscope at 500x magnification using a pair of X,Y,Z-microtranslation stages as shown in Fig. 1.

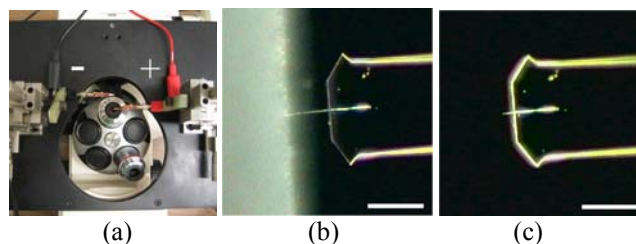


Figure 1: (a) Digital micrograph of the experimental apparatus for fabrication of individual MWNT-microstructure cathodes, showing electrical connections to a pair of XYZ-translation stages over an inverted optical microscope. The positive electrode is connected to the stage supporting the Ni-coated Si microstructure while the negative electrode is attached to the stage supporting the CNT cartridge. Optical micrographs of the attachment process of a MWNT to a Ni-coated Si microstructure: (b) transfer of an individual MWNT to a microstructure and (c) electrically induced detachment of the MWNT from the source. Scale bars in (b) and (c) each represent 20 μm .

Two different types of cathode support structures are fabricated and used in this study, one using an etched Ni wire (Fig. 2a) and the other a Ni-coated Si microstructure (Fig. 2b). For the cathode shown in Fig. 2b we have observed reproducible and stable emission current greater than 200 nA thus demonstrating the feasibility of this

device for application as electron point source for advanced scanning electron microscopy.

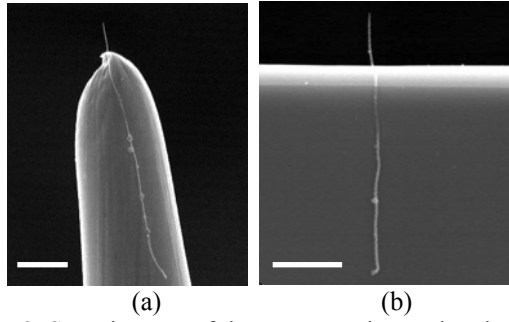


Figure 2. SEM images of the two experimental cathodes: a) Cathode 1 with a MWNT attached to an etched hemispherical Ni wire and b) Cathode 2 with a MWNT attached to a Ni-coated Si microstructure. Scale bars are 2 μm .

3 MODELING

In order to investigate the fundamental field properties of CNT cold field emitters a Technology Computer Aided Design (TCAD) modeling technique was developed using the field emission data of the cathodes shown in Fig. 2. This computational methodology has proven to be capable of investigating the large-scale integration of individual CNT field emitters. This capability enables the realization of structural optimization and thus the design of efficient CNT-based electron guns suitable for macroscale system integration.

The two experimental structures in Figs. 2 exhibit very different macroscopic turn-on fields of 1.6 and 2.5 V/ μm , even though both structures incorporate CNTs with similar geometries. The effect of overall cathode structure on the electrostatic fields at the tip of the nanoscale emitter is investigated using TCAD. The analogous TCAD structures, Cathode 1T and 2T, corresponding to experimental Cathode 1 and Cathode 2 are shown schematically in Fig. 3a.

The variation of electric field at the emitter tip as a function of applied voltage for the two cathodes in TCAD simulation are shown in Fig. 3b. The results clearly demonstrate that the different support geometries greatly influence the electrostatic field of the emitter tip. These results also exhibit a trend similar to those observed in the experimental data. Figure 3c shows emission current as a function of applied voltage obtained from the simulations as well as experiments. For a typical microscopic turn-on field of 1×10^9 V/m at the nano-scale emitter tip [5, 6], macroscopic turn-on fields of 1.4 and 2.4 V/ μm are obtained for Cathodes 1T and 2T, respectively. These values are in good agreement with the experimental data of Cathodes 1 and 2.

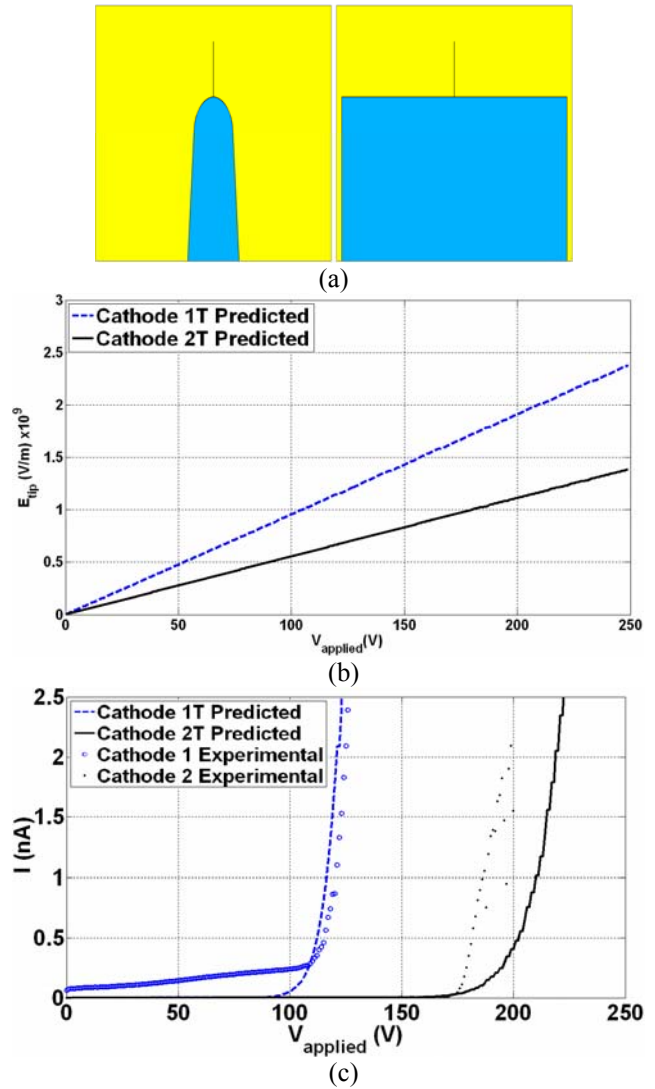


Figure 3. (a) Schematic representation of cathode structures 1T and 2T. (b) Microscopic tip field, E_{tip} versus applied voltage, V_{applied} derived from TCAD simulation for Cathodes 1T and 2T. (c) I-V plots of experimental Cathodes 1 and 2 together with their predicted I-V plots based on the TCAD derived values of E_{tip} .

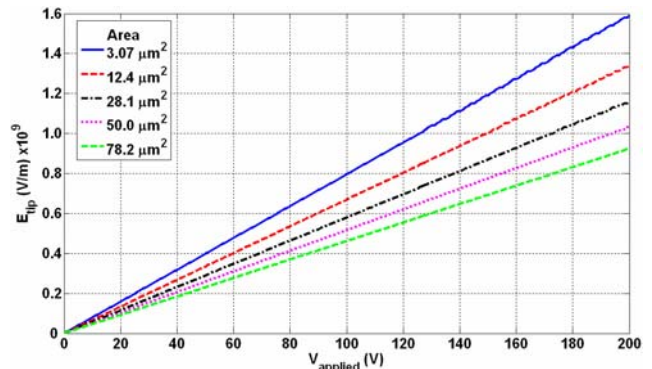


Figure 4. TCAD derived E_{tip} as a function of V_{applied} for a cathode structure similar to that of Cathode 2T with varying top surface area of the cylindrical support structure.

We further investigate the effect of support structure area on the microscopic tip field. As shown in Fig. 4, increasing this area in Cathode 2T from $3.07 \mu\text{m}^2$ to $78.2 \mu\text{m}^2$ decreases the tip electric field, E_{tip} . The field enhancement factor, β , extracted from the slopes of the plots in Fig. 4, decreases non-linearly with an increase in the support structure area. Consequently, for the variation in area mentioned above, the turn-on voltage increases by about 100 V.

4 SYSTEM ARCHITECTURE

Both experimental and TCAD results discussed above demonstrate that the ancillary structure of a cathode greatly affect the field emission characteristics of a CNT emitter. For applications in electron microscopy, it is necessary to integrate the individual CNT cathode with other system components such as a Wehnelt grid for extraction of electrons. This configuration is commonly referred to as the electron gun. Optimization of this integrated system requires detailed investigation of structural parameters such as cathode-Wehnelt grid separation, grid diameter, and the aspect ratio of CNT emitters. Simulation results in this study demonstrate that the TCAD technique employed is an effective tool for achieving such optimization.

5 CONCLUSION

From the results obtained in this work it can be concluded that the magnitude of the microscopic field decreases with increasing area of the cathode supporting structure. We have also presented quantitative evidence that the effect of supporting cathode structure geometry must be considered in the analysis of field emission properties of nanoscale emitters. Furthermore, TCAD has proven to be an effective tool for investigating the multi-length scale integration of nano-scale emitter. This computer aided technique is capable of exploring the challenges presented by large-scale integration of a point electron source with added ancillary structures present in an electron beam system.

6 REFERENCES

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