Optimizing Carbon Nanotube Field Emission Cathodes: Height-Dependent Performance and Emission Enhancement

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Introduction

Cathodes are a fundamental component in electron emission devices, serving as the source of electrons for applications such as hall effect thrusters and electron microscopy.

Field Emission Cathodes

Field emission cathodes (FECs) offer a compelling alternative to thermionic cathodes by leveraging quantum tunneling to extract electrons utilizing electric fields to narrow the potential barrier. This enables:

- **Lower power consumption**
- **Better efficiency**
- **Smaller, micro scale devices**

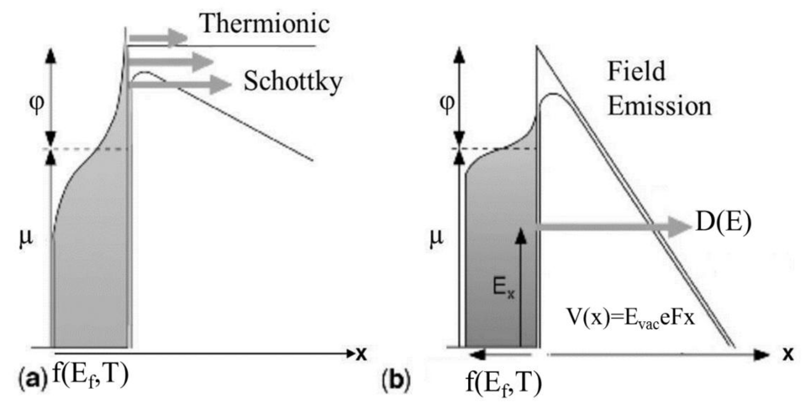

Figure 1: Potential barrier mechanism for a.) thermionic vs b.) field emission [1]

$$J = \frac{a E_{loc}^{2}}{t^{2}(y)\,\varphi} exp\left(-\frac{b\varphi^{\frac{3}{2}} v(y)}{E_{loc}}\right) \qquad E_{loc} \sim \beta$$

Figure 2: Fowler-Nordheim equation that describes the relationship between emitted current density **J** and **localized** electric field [1]

The localized electric field is dependent the field enhancement factor β; **carbon nanotubes (CNTs) maximize the β due to their high aspect ratio** geometry, significantly **lowering** the threshold electric field necessary for tunneling.

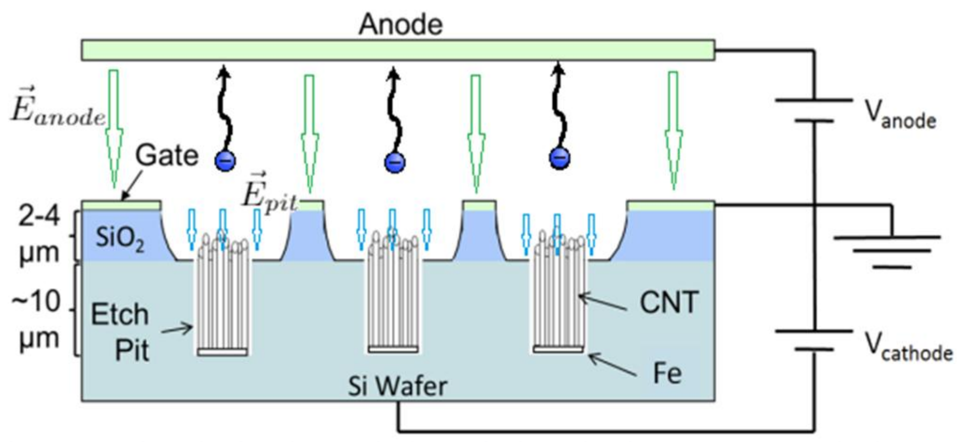

Figure 3: Electrical Schematic for spindt cathode CNTFEC emission mechanism

The goal of this study is to **optimize free current** generation of spindt cathode configurations of Carbon nanotube field emissions cathodes (**CNTFECs**) through **controlling the growth height of carbon nanotubes.**

Methods

By testing fabricated samples, experimental emission current data was collected, while COMSOL simulations enabled the optimization of device dimensions to enhance performance. These insights guide the fabrication of future samples with improved efficiency and higher emission current.

Fabrication and Testing

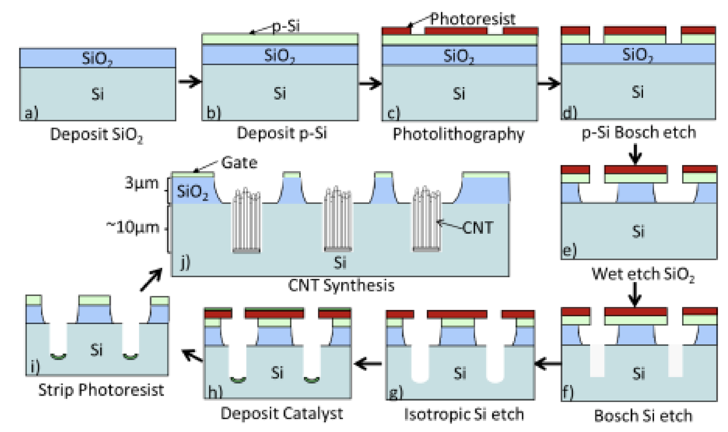

Figure 4: Fabrication cross-section

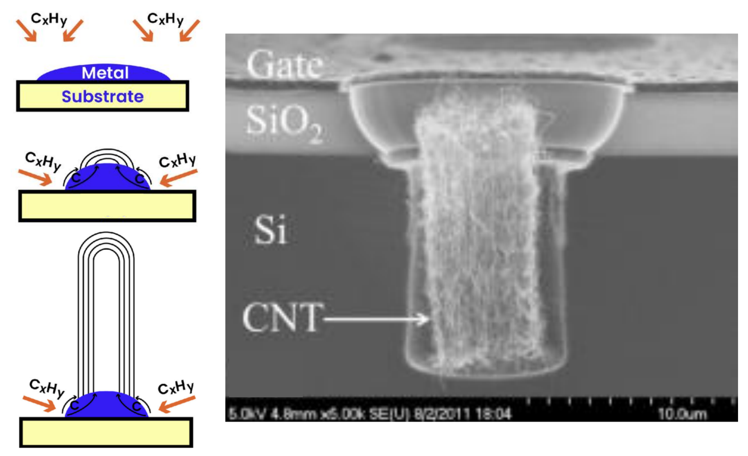

Figure 5: SEM image of fabricated emission pit [1]

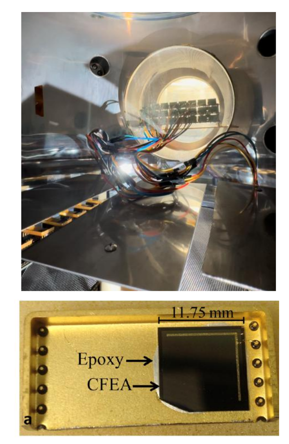

Figure 6: Current emission test setup

CNTFEC COMSOL Simulation Setup

- **1:1 ratio** to fabricated sample dimensions, ensuring accurate comparisons between simulation and experimental results.
- CNT **heights** and **voltage** biases were **parametrically swept to find maximized localized electric field** and therefore maximized free electron density.
- Simulation results were fitted to experimental data, and the **optimal CNT height** for this configuration was deduced.

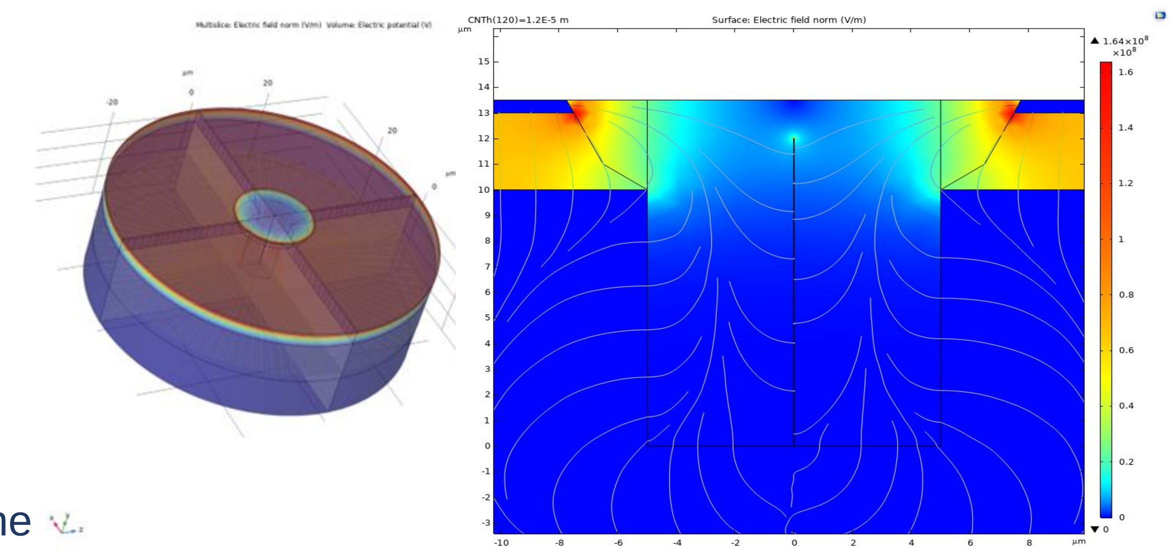

Figure 7: 3D and 2D cross-section modeling of CNTFEC within COMSOL

Results

CNT Height vs. Localized Electric Field

- ~6 µm is the safest fabrication parameter for CNT height, as any longer CNTs resulted in lower yield due to shorting
- Simulations involved systematically varying the CNT height within practical fabrication limits.
- The localized electric field at the emission point was extracted for each CNT height
- Results showed a clear optimal CNT height ~11 µm where the localized electric field reaches a maximum.

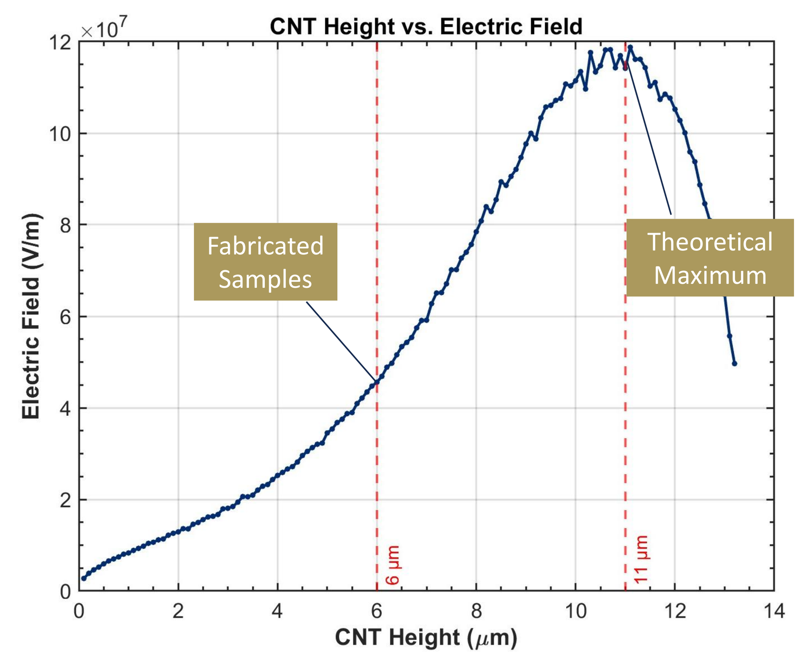

Figure 8: CNT Height vs E-Field at Emission point; substrate Bias at max -240V

Fitted Field Emission for 6 µm CNT Height

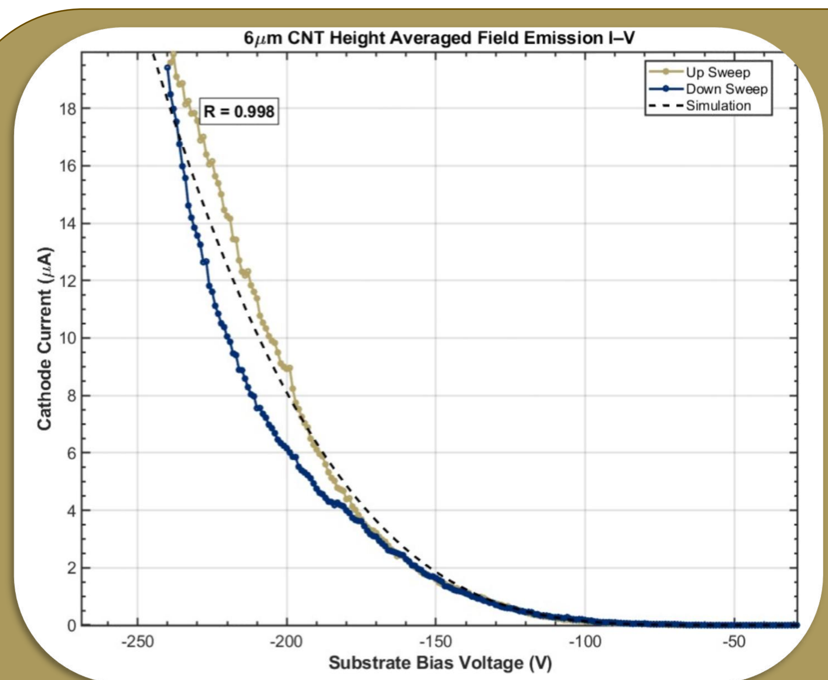

Figure 9: Fitted dashed COMSOL simulation results for 6µm CNTs

- Field emission data for CNT samples with a height of 6 µm was fitted using standard the **Fowler-Nordheim** emission current density equation.
- Experimental emission currents closely matched simulation results, as indicated by a high correlation coefficient **R = 0.998**.
- This agreement validates the simulation model, confirming its accuracy in **predicting CNT field emission performance** and allowing for **extrapolation of optimized CNT heights** to maximize emission current

Conclusions

Current CNTFECs are grown with 6 µm of CNTs for fabrication reliability. However, advancements in PECVD growth techniques enable the fabrication of taller, more uniformly aligned CNT structures within CNTFEAs, offering the potential for enhanced emission performance.

Through simulations verified by experimental results, an optimized CNT height of **11 µm** was identified, resulting in a **~10× increase in field emission current** at the max substrate bias of -240 V compared to conventional 6 µm CNTs.

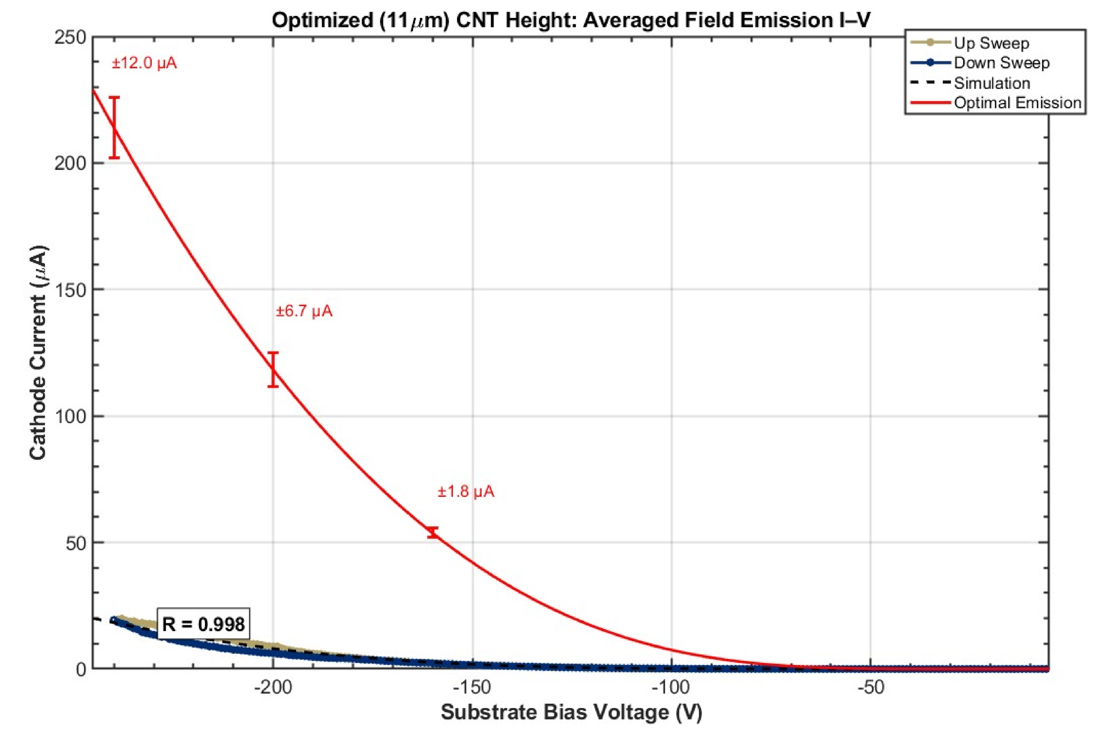

Figure 10: Emission current given optimization of CNT height

Despite achieving these promising, optimized results, **fabrication constraints** may limit the feasibility of maintaining stable CNTs at heights approaching ~11 µm, primarily due to their relative **proximity to the gate layer**.

Future work will address these trade-offs and **experimentally explore strategies to increase field emissions current** based on the insights from this research. Specifically, efforts will focus on **precisely controlling the growth of vertically aligned CNTs** within a spindt cathode configuration to further optimize device performance.

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