Energy Exchange During Electron Emission from Carbon Nanotubes: Considerations on Tip Cooling Effect and Destruction of the Emitter

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1. Introduction

One important challenge:

Many plasma-based processes may become cost-effective if the power of the discharge could be increased.

Our objectives:

Avoid the melting of the cathode by optimizing the distribution of the current on the surface.

Maximize the accessible $<J>$. 

For arc discharges:

$$J \approx 10^{9-10} \text{ A/m}^2$$

- High temperature
- Local melting
- Strong erosion at high power
2. Theory: electron emission

- Electron emission

  - Murphy and Good theory (M-G)
  - 2 simplifications:
    - Fowler-Nordheim (field effect)
    - Richardson-Dushman (temperature-driven)

Limited validity:
For significant $E_s$ and $T_s$ only M-G theory applies.
3. Optimized geometry

Tip effect:

The surface field $E_s$ is enhanced at the CNT tips.

$\beta$ = field enhancement factor

$$\beta = \frac{E_s}{\Delta V/d}$$

Isolated CNT

Array $\rightarrow$ $\beta$ decreases with the spacing $\Delta x$. $\rightarrow$ $\Delta x_{\text{optimal}} \propto h$

$\beta \gg 1$ $\rightarrow$ Enhanced field emission at low $\Delta V$. $\rightarrow$ For $\beta \gg 1$: Less emitters per m$^2$.

$$(h/r) \gg 1$$

If $h$ increases, $\Delta x_{\text{optimal}}$ (m) is larger.

Stronger field

$E_s(\Delta V/d)$

$$(\Delta V/d) = \text{applied field}$$

Enhanced field emission at low $\Delta V$. $\rightarrow$ $\Delta x_{\text{optimal}} \propto h$

For $\beta \gg 1$: Less emitters per m$^2$.
4. Results: electron emission and energy conservation

Electrons can heat higher states if heating? $T_s$.

Replacing electrons all come with $\varepsilon = \varepsilon_F$.

Strong $E_s \rightarrow$ Electrons are emitted from $\varepsilon < \varepsilon_F$ states too.

High $T_s \rightarrow$ Many candidates on $\varepsilon > \varepsilon_F$ states.

The energy balance: $\langle \text{Energy} \rangle - \text{Fermi Energy}$

Emitted electrons (tunnel effect) can be occupied.

At $T_s = 0$ K: the last occupied state.

Cooling

Stronger $E_s$

Occupied energy levels

Thinner potential barrier

Finite potential barrier

$\varepsilon_F$

Fermi energy

$E_s$

Montreal effect

Cooling >>> Heating?

Cooling <<< Heating?
4. Results: the Nottingham effect

- M-G theory:
  - Complex nonlinear expressions.
  - Elliptic integrals.
  - Requires numerical integration.

**Typical situation:**

M-G theory is replaced. Wrong.

- No valid approximation of \( \epsilon_{Not} \)
- Fowler-Nordheim (field effect)
- Richardson-Dushman (temperature-driven)

In our source: \( \epsilon_{Not} = 1.5 k_B T \) was assumed (not true).

\[
\epsilon_{Not} = \frac{e}{J_{M-G}} \int_{-\infty}^{\infty} (...) dE + \phi_0
\]
4. Results: the Nottingham effect

\[ 1.5 \, k_B T = 0.25 \, \text{eV} \]
4. Results: theoretical performances

Our 3-D model:
Calculates $\beta$ above the emitters.
For accepted electrical and thermal CNT properties:
Calculates $J(x,y,z)$ and $T(x,y,z)$ in the electrode.

What are the limits?
CNT are etched by O$_2$:
- 800-1000 K (in air)
- 1500-2000 K (in vacuum)

For the experimental data: 2000 K

What are the limits?

$10^{10}$ A/m$^2$ is possible if $\Delta x=h_{\text{CNT}}=100$ nm

Our suggestion:
$T_{\text{acceptable}} < 600$ K.

3 cases:
$(h/r)_{\text{CNT}}=5, 20$ and 100

$T=600$ K
Theoretical limit reached

$T=3000$ K

$T=2000$ K
Prediction of the breaking point.

4. Results: evolution of $\varepsilon_{Not}$

Possible cooling for $(h/r)_{CNT}=100$

Peaked profiles from 1500 K

2 trends

Initial heating
4. Results: comparison with experiments

- The destruction mechanism for CNT electron emitters at high current.
  - Long CNT: accurate prediction of the breaking point location at the tip.
  - Short CNT: no tip cooling effect, rapid increase of temperature above 2000 K.

Assumption of the authors: $\varepsilon = 1.5k_B T$ (always positive; no heating besides Joule effect).

Unexplained: CNT on W microtips, high vacuum.

Long CNT are cooled at their tips.

Short CNT are heated instead and burn sooner than expected.

5. Conclusions

- A promising theoretical design for strong emission at low temperatures was selected.
- Alumina templates are compatible substrates for the best geometry.
- The Nottingham effect plays an important role in the destruction of CNT electron emitters.
- Our model explains the different trends for the destruction of long and short CNT during electron emission.
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