High brightness of field emitted electron beam from graphene edges

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For NDHU Physics 13/03/2017
Introduction & Motivation
- Thin film edge is very sharp
- CNT vs. Graphene
- Why graphene emitter

Experiment
- Emitter preparation
- Field emission from graphene edge

Results and Discussion
- Calibrate magnification of field emission microscope
- Field emission microscope (FEM) from graphene

Summary
PART ONE

Introduction & Motivation
Field Emission

- Electrons released from a object (emitter, usually metals) by intense electric field.
- Quantity of releasing electrons relates to the emitter’s work function & local Field

Pikachu releases electric at 100 KV
FE from ta-C thin film edge: Process approach

(a) Cross-section view

(b) Plan view

(c) RIE

(d) Photoresist

Si₃N₄
Pt-C
Si

Si₃N₄
Pt-C
Si

Pt-C
Si

Si₃N₄
Pt-C
Si

Si₃N₄
KOH
Si
Self-assembled thin film edge emitter (SATFEE)
Simulations

Self-Assembled Thin Film Edge Emitter: STRUCTURE

3D_Bimetal7: Grid#1 p2 Nodes=2217 Cells=1227 RMS Err= 5.8e-6

00:09:27 11/30/01 FlexPDE 2.21b

Shape
ZOOM(0,0,0,3,3,3)
(-39.3,-95.7, 30.)

01:08:45 11/29/01
FlexPDE 2.21b

Integral=  8848.679

integral= -3.595457e+12

X
-10.0
-5.0
0.0
5.0
10.0

Z
-10.0
-5.0
0.0
5.0
10.0
15.0
20.0

Z-stress
on y=high/2

1.10
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
-0.40
-0.50
-0.60
-0.70
-0.80
-0.90
-1.00
-1.10

Scale = E13
Cr backbone SATFEE
Discovery of CNT

**Nature 354, 56 - 58**  
(07 November 1991)  
Helical microtubules of graphitic carbon  
SUMIO IIJIMA

**Science** Vol 270, Issue 5239  
(17 November 1995)  
A Carbon Nanotube Field-Emission Electron Source  
Walt A. de Heer, A. Châtelain, D. Ugarte

**Japanese Journal of Applied Physics**  
Volume 36, Part 2, Number 10A, 1997  
Field Emission Patterns from Single-Walled Carbon Nanotubes  
Yahachi Saito, Koji Hamaguchi, Tetsuo Nishino, Koichi Hata, Kazuyuki Tohji, Atsuo Kasuya and Yuichiro Nishina
Further attempts: CNT Emitter

*free standing* + *thin film*

*edge* + CNT lateral field emission high speed diodes

Glass substrate, free standing edge and bridge, Cr electrodes
Confine CNT deposition on free-standing thin film edge
Leakage current and breakdown voltage carbon nanotubes field emission diode

Breakdown voltage: 700V
Leakage current: ~$10^{-10}$ A

Low leakage current below 600 V

Breakdown voltage: 700 V
Characteristics of carbon nanotubes field emission diode on reactive on/off time

Reactive on time: <10 ns

Turn-off time: < 100 ns
Rectification and Reverse recovery time test

Fabrication of *novel* electrodes for plasma educed backlight module

- A mixture of phosphors power and CNT as the screen printing paste.
- Attached each other by non-UV absorbing binder.
- Large area screen.
- AC pluses operation.
- High or medium pressure of plasma.
Plasma Ignition condition

- Experimental: CNT + CRT (green) phosphors on ITO with bp55 (binder)
- Control: ITO only

<table>
<thead>
<tr>
<th></th>
<th>Ignition pressure</th>
<th>Ignition flow</th>
<th>Ignition voltage</th>
<th>Min. stable voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.</td>
<td>9.8 E-3 torr</td>
<td>12 sccm</td>
<td>476 V</td>
<td>117 V</td>
</tr>
<tr>
<td>Ctl.</td>
<td>1.2 E-2 torr</td>
<td>29 sccm</td>
<td>840 V</td>
<td>445 V</td>
</tr>
</tbody>
</table>
Assembly and package

1. Optimized CNT wt%
2. Thin: only 7 mm
3. Advantages
   a. Low op. V: 210 V
   b. Low pr. consumption: 20 mW
   c. Brightness to 1000 cd/m²
Lighting test

(b) Glass spacer
Visible emission
Ar plasma (behind the cathode plate)

Ar based  Xe based

Single tube emitter

High brightness electron beam from a multi-walled carbon nanotube

Niels de Jonge, Yann Lamy, Koen Schoots & Tjerk H. Oosterkamp
High brightness electron beam from a multi-walled carbon nanotube

Niels de Jonge, Yann Lamy, Koen Schoots & Tjerk H. Oosterkamp
Brightness measurement (II)

\[ x(n) - x(0) = z_2 \sqrt{\frac{2\lambda}{z_1}} \left( \sqrt{n + \frac{3}{8}} - \sqrt{\frac{3}{8}} \right) ; \quad n = 0, 1, 2, \ldots \]

, 其中 \[ x(0) = z_2 \sqrt{\frac{2\lambda}{z_1}} \frac{3}{8} \]

\[ x(N) = z_2 \sqrt{\frac{2\lambda}{z_1}} \left( \frac{N + \frac{3}{8}}{8} \right) \]

\[ \lambda = \frac{h}{p} = \frac{h}{m_e v} = \frac{h}{m_e \sqrt{\frac{2eU}{m_e}}} = \frac{h}{\sqrt{2m_e eU}} \]

Applied anode voltage: 50V

\[ \lambda = 0.17 \text{ nm} \]

\[ \rightarrow Z_1 = 3.9 \mu m \rightarrow \text{magnification} \]

\[ M = \frac{Z_2}{Z_1} = 4.1 \times 10^4 \]

\[ Z_2 = 16 \text{cm} \]
\[ N = 7 \]
\[ x(N) = 4 \text{mm} \]

Virtual source radius \[ r_v = \frac{\lambda Z_2}{\pi x(N)} \]

\[ r_v = 2.1 \text{ nm} \]

\[ B_r = 3.6 \times 10^9 \text{ Am}^{-2} \text{sr}^{-1} \text{V}^{-1} \]

High brightness electron beam from a multi-walled carbon nanotube

Niels de Jonge, Yann Lamy, Koen Schoots & Tjerk H. Oosterkamp
Graphene emitter (1)

Field emission from graphene based composite thin films
Goki Eda, H. Emrah Unalan, Nalin Rupesinghe, Gehan A. J. Amaratunga and Manish Chhowalla

Improved electron field emission from morphologically disordered monolayer graphene

Srikrishna Pandey, Padmnabh Rai, Shashikant Patole, Fethullah Gunes, Gi-Duk Kwon, Ji-Beom Yoo, Pavel Nikolaev and Sivaram Arepalli
Why Graphene Emitter: energy dispersion aspect

\[ N(\omega, E) d\omega dE = n(E) dE \frac{|v| \cos \theta}{4\pi} \sin \theta d\theta d\phi \]

(number arriving at \( \theta \) per solid angle)

\( \propto \) (differential solid angle).

where
Klein tunneling model of low energy electron field emission from single layer graphene sheet

Klein tunneling coefficient $T_c$ as a function of incident angle $\phi$ at various local electric field $F$.

Experiment
Emitter preparation
Field emission from graphene edge
Mechanical cleavage
Epitaxial growth on silicon carbide


Graphene by Oxidation Reduction


CVD
Facile Quenching Method

HOPG

Rapidly heated to 1000 °C within 5 min.

Hot HOPG

Fast quenched to room temperature in a bath of cool water containing 1.0 wt % ammonium hydrogen carbonate (NH$_4$HCO$_3$).

NH$_4$HCO$_3$(l) $\rightarrow$ NH$_3$(g) + CO$_2$(g) + H$_2$O(g)

Graphene
Graphene sheets was formed on the top of the solution.
The graphene layer can be found at the edge of copper grids, which can be attached by tungsten probe later under OM observation.
Raman Spectrum of single-layer graphene


Raman spectrum


Chamber

Phosphor screen

emitter

Agilent 34405a

R = 10kΩ

Power supply
Tip to Screen Distance=350μm, turn-on field = 2.84 V/μm
F-N plot

<table>
<thead>
<tr>
<th># of Conditioning</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turn on Voltage</td>
<td>1750V</td>
<td>1365V</td>
<td>1050V</td>
</tr>
</tbody>
</table>

First time

Second time

Third time
Stability 4.8%
Field Emission Microscope (FEM)


http://www2.nsysu.edu.tw/physdemo/docs/exp4/exp4doc1.doc
FEM from CNTs


FEM image

Multi-layer graphene

Single-layer graphene
Single-layer graphene

\[ \text{Picture Image:} \begin{cases} \text{One pixel} = 2.205\mu\text{m} \\ \text{Point to Point} = 9.5 \text{ pixel} \end{cases} \implies \text{Image distance} = 20.95\mu\text{m} \]

\[ \text{Real distance} = 1.23\text{Å} \times 2 = 2.46\text{Å} \]

\[ \text{Magnification} = \frac{\text{Image distance}}{\text{Real distance}} = \frac{20.95\mu\text{m}}{2.46\text{Å}} = 8.5 \times 10^4 \]

Multi-layer graphene

\[ \text{Picture Image:} \begin{cases} \text{One pixel} = 5\mu\text{m} \\ \text{Line to Line} = 19 \text{ pixel} \end{cases} \implies \text{Image distance} = 95\mu\text{m} \]

\[ \text{Real distance} = \frac{\text{Image distance}}{\text{Magnification}} = \frac{95\mu\text{m}}{8.512 \times 10^4} = 11.16\text{Å} \]

\[ \text{Graphene layers} = \frac{11.16\text{Å}}{3.37\text{Å}} \approx 3 \text{ layers} \]

Remarkable current density = \(10^{10}\text{A/cm}^2\) from single layer graphene
For STM application

- Pre-activate graphene probe.
- Pre-selection of sharpness by Raman spectrum for the better resolution.
<table>
<thead>
<tr>
<th>3D image</th>
<th>Probe</th>
<th>Horiz. distance</th>
<th>Vert. distance</th>
<th>V/H</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>(I)</td>
<td>Blunt probe</td>
<td>587nm?</td>
<td>26.7nm</td>
<td>0.0455</td>
<td>No good</td>
</tr>
<tr>
<td>(II)</td>
<td>Sharp probe</td>
<td>645nm</td>
<td>36.6nm</td>
<td>0.0567</td>
<td>Fair</td>
</tr>
<tr>
<td>(III)</td>
<td>Graphene probe (non activated)</td>
<td>626nm</td>
<td>64.3nm</td>
<td>0.1027</td>
<td>Good in 1/3 image</td>
</tr>
<tr>
<td>(IV)</td>
<td>Graphene probe (activated)</td>
<td>628nm</td>
<td>72.5nm</td>
<td>0.1154</td>
<td>Good</td>
</tr>
</tbody>
</table>
Tool: thermal CVD; Source: camphor - we get nice graphene

<table>
<thead>
<tr>
<th></th>
<th>G-band</th>
<th>2D-band</th>
<th>D-band</th>
<th>$\frac{I_G}{I_{2D}}$</th>
<th>$\frac{I_G}{I_D}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>峰值位置 (cm$^{-1}$)</td>
<td>1585</td>
<td>2703</td>
<td>X</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>峰值強度</td>
<td>2929</td>
<td>7609</td>
<td>0</td>
<td>0.38</td>
<td>X</td>
</tr>
</tbody>
</table>
Commercial e-beam source

E-gun in SEM

- Emitter
- Heater
Graphene e-gun

Gun tip in SEM: sharp edges with high carbon content

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight (%)</th>
<th>Atomic (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>63.66</td>
<td>90.26</td>
</tr>
<tr>
<td>Cu</td>
<td>36.34</td>
<td>9.74</td>
</tr>
<tr>
<td>Totals</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>
Measurement tool

Chamber: $10^{-7}$ torr
Results and Discussion
Anode to cathode distance is calibrated by piezo drive movement converting to the pixel pitch on the photo.

\[
2x = 32.30 \text{ pixel}
\]
\[
2(x + 100) = 48.08 \text{ pixel}
\]
\[
x = 202.77 \, \mu\text{m}
\]
Thermal-Field emission (2)

I-V measurement

Turn-on field: 8.21 V/μm

F-N diagram to field enhancement factor β: 593.95
Thermal-Field emission (3)

Graphene probe vs. Pure Cu

Graph showing current (A) vs. electric field (V/μm) with two probes: G-Cu probe and Cu probe. The turn-on field is indicated at 8.21 V/μm and 16.25 V/μm.
## Emission patterns

<table>
<thead>
<tr>
<th>Screen voltage</th>
<th>2200 V</th>
<th>2600 V</th>
<th>3000 V</th>
<th>3400 V</th>
<th>3800 V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>G-probe</strong></td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Cu</strong></td>
<td><img src="image6.png" alt="Image" /></td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Brightness measurement (1) – position beam

Current changes to locate center of the anode

12V
20W

Current changes to locate center of the anode

<table>
<thead>
<tr>
<th>anode current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.0E-6</td>
</tr>
<tr>
<td>5.0E-6</td>
</tr>
<tr>
<td>4.0E-6</td>
</tr>
<tr>
<td>3.0E-6</td>
</tr>
<tr>
<td>2.0E-6</td>
</tr>
<tr>
<td>1.0E-6</td>
</tr>
<tr>
<td>0.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>
Brightness measurement(2) – Interference

N = 2
x(N) = 3.5mm
Brightness measurement (3) – Angular current

\[ B_r = \frac{I'_r}{\pi r_y^2} \]
\[ I'_r = \frac{I'}{U} \]
\[ I' = \frac{dI}{d\Omega} = \frac{I}{\Delta \Omega} \]

- **Anode voltage**
- **Acc. voltage (5000V)**
- **100MΩ**

\[ I = \frac{V}{R} = 2.45 \times 10^{-7} \text{ A} \]
\[ \Delta \Omega = \frac{A}{r^2} = 6.44 \times 10^{-2} \text{ sr} \]
\[ I' = 3.81 \times 10^{-6} \text{ Asr}^{-1} \]
\[ I'_r = \frac{I'}{U} = 7.62 \times 10^{-10} \text{ Asr}^{-1} V^{-1} \]

- **207.29mm²**
- **r=56.75mm**
$I_r' = 7.62 \times 10^{-10} \text{ A sr}^{-1} \text{V}^{-1}$

U(anode voltage) = 650V
U(Acc. voltage) = 5300V
$Z_2 = 24 \text{mm}$
$N = 2$
$x(N) = 3.5 \text{mm}$

$$\lambda = \frac{h}{\sqrt{2m_e e U}} = \frac{6.6 \times 10^{-34}}{\sqrt{2 \cdot 9.1 \times 10^{-31} \cdot 1.6 \times 10^{-19} \cdot 650}} = 4.80 \times 10^{-11} \text{ m}$$

$$r_v = \frac{\lambda z_2}{\pi x(N = 2)} = \frac{4.80 \times 10^{-11} \cdot 2.4 \times 10^{-2}}{\pi \cdot 3.5 \times 10^{-3}} = 1.05 \times 10^{-10} \text{ m}$$

$$B_r = \frac{I_r'}{\pi r_v^2} = \frac{7.62 \times 10^{-10}}{\pi \left(1.05 \times 10^{-10}\right)^2} = 2.20 \times 10^{10} \text{ Am}^{-2} \text{ sr}^{-1} \text{V}^{-1}$$
Comparison of brightness from various emitters

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Material</th>
<th>Brightness (A/sr. m². V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>W</td>
<td>10⁵</td>
</tr>
<tr>
<td>Thermal</td>
<td>LaB₆</td>
<td>10⁶</td>
</tr>
<tr>
<td>Field</td>
<td>W(310)</td>
<td>2 x 10⁸</td>
</tr>
<tr>
<td>Schottky field</td>
<td>ZrO/W(100)</td>
<td>10⁸</td>
</tr>
<tr>
<td>Cold field</td>
<td>CNT</td>
<td>3.6 x 10⁹</td>
</tr>
<tr>
<td>Thermal Field (this work)</td>
<td>Graphene</td>
<td>2.2 x 10¹⁰</td>
</tr>
</tbody>
</table>
Summary

• We demonstrated a simple and low-cost process to fabricate an individual free-standing graphene emitters and characterizing their field-emission properties.

• Very first time to observe the FEM image of graphene edge and demonstrated only few atoms response for electron emission from the edge of single-layer graphene.

• Field screen effect was also observed at 3-layer graphene edge.

• From CVD graphene emitter, we conclude the virtual source radius is $1.05 \times 10^{-10}$ m, it generate the electron beam in brightness $2.20 \times 10^{10}$ A$m^{-2}sr^{-1}V^{-1}$, which higher than CNT emitter.
VML 2016 gathering
Thank you for your attention
Future Work 1: Cut graphene & select direction

Mode = Tapping mode, Tip bias = -35V

Before

After
Future work 2: Using GaSe monolayer for FE
OM: thick layer of GaSe measure the thickness from AFM
Single layer of GaSe confirm by AFM step height
Raman

![Graph showing Raman shift vs. intensity with peaks labeled 221, 212, 315, 308, 251, 303, and 215. The graph compares bulk and single layer samples at T = 300 k and λ_{exc.} = 514.5 nm.]