Field Emission Cathodes made from Laser Cut CNT Fibers and Films

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Integrity ★ Service ★ Excellence

Motivation

Improved Materials for High Power Vacuum Electronic Devices

- Advanced ***Cathode*** Materials needed to produce stable high current electron beams
- High power, high frequency operation is required

- Current SOA cathodes are thermionic
- Requires high temperature operation-increased outgassing
- Cooling requirements lead to added system complexity and weight

- ***Anode*** Materials – efficient beam collection
- SEE and desorbed H can cause impedance collapse in the vacuum gap

Field Emission Cathodes

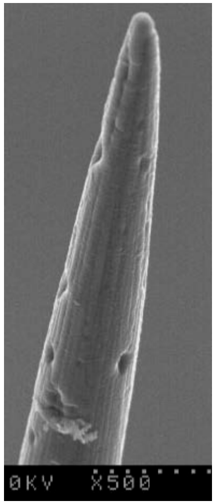
Field Emission cathodes preferred over thermionic

- Rely on electron tunneling instead of material heating for electron emission
- Thus no need for cooling
- Narrow energy spread in electron beam

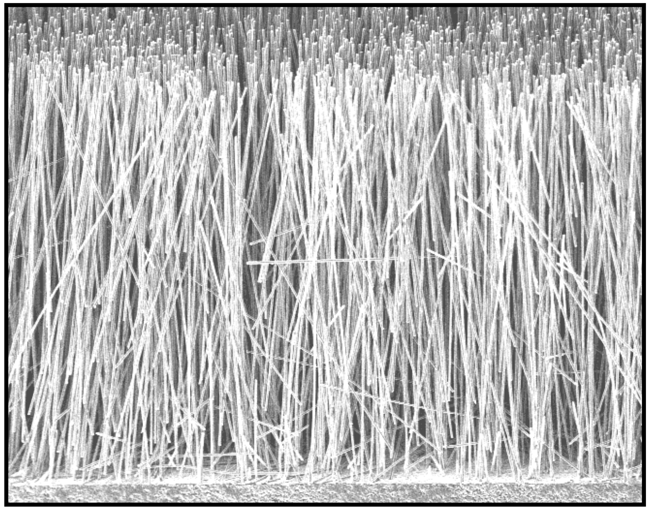
Graphite Fiber

- Field Enhancement (~ *h/r*)
- Works great for pulsed power applications

D. Shiffler, et al. IEEE Transactions on Plasma Science. Vol. 36, No. 3, June 2008



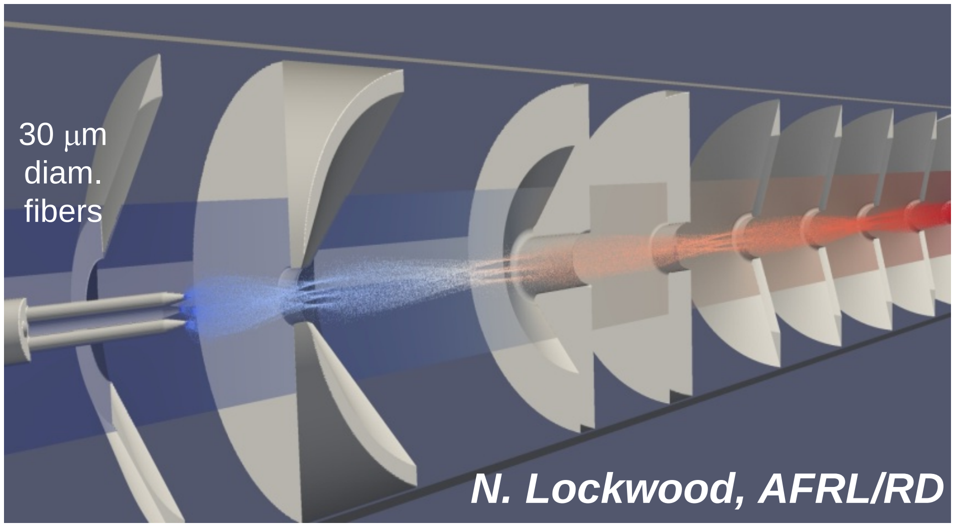
30 μm diam. graphite fiber



graphite fiber carpet

DC Cathodes

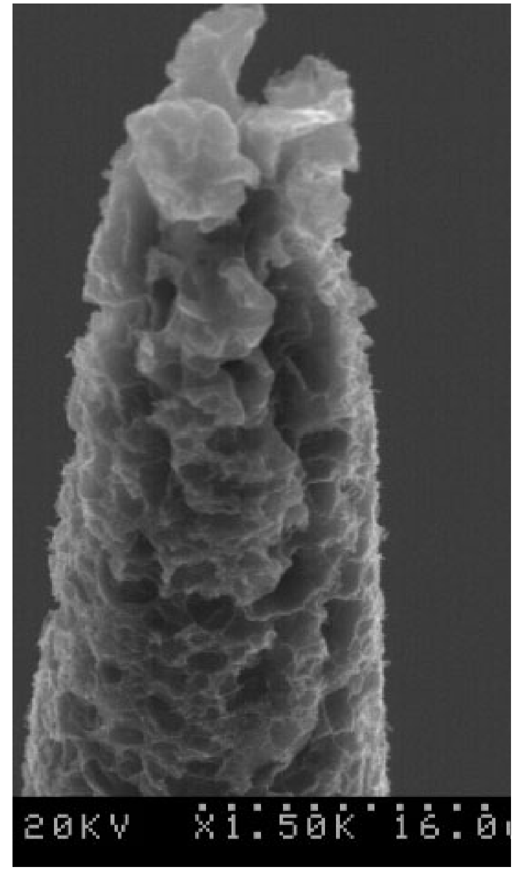
Fiber Array Cathode for Electron Gun



– Goal is to get 10 mA of DC current from small fiber array

– Graphite Fibers fail due to Joule heating at low currents

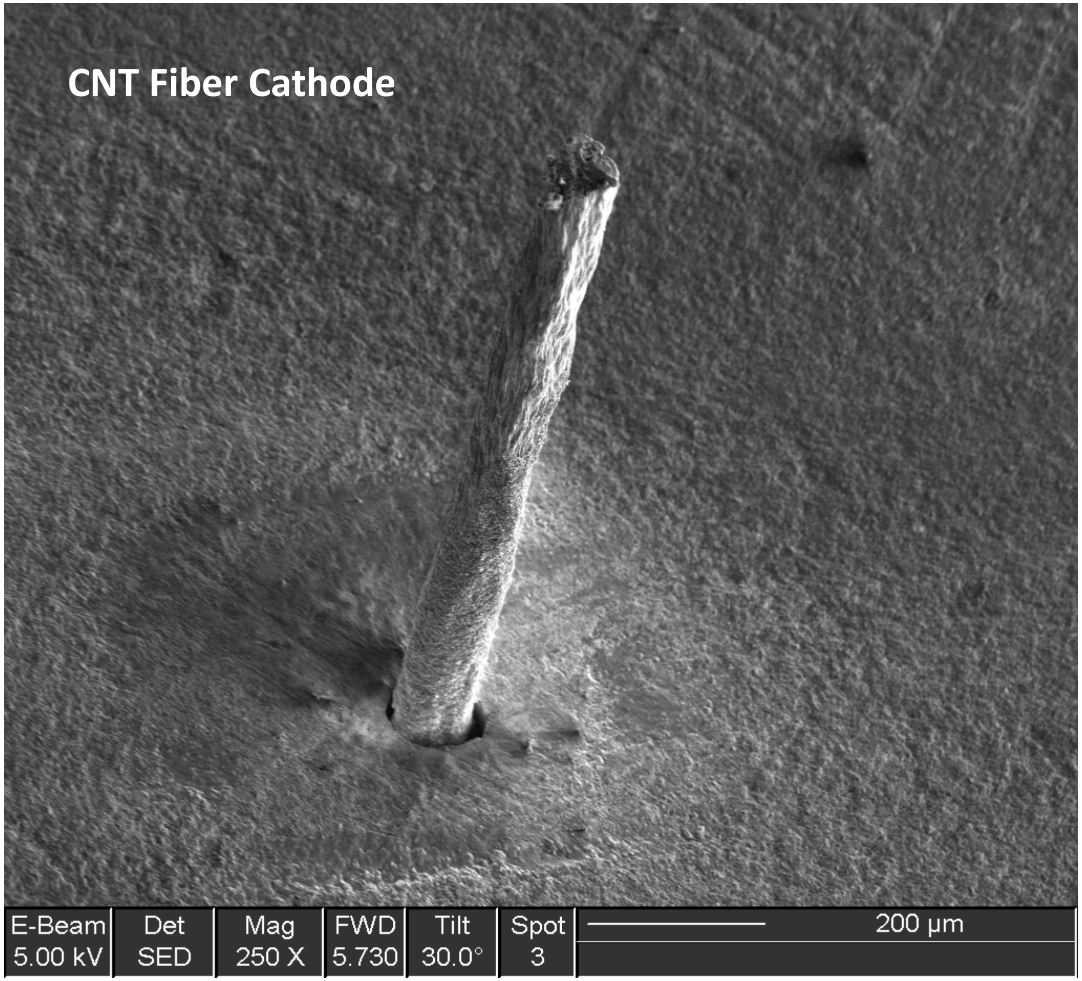
Graphite Fiber Cathode

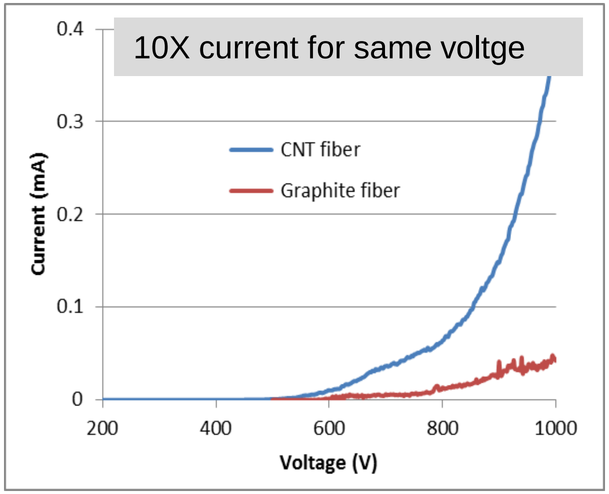


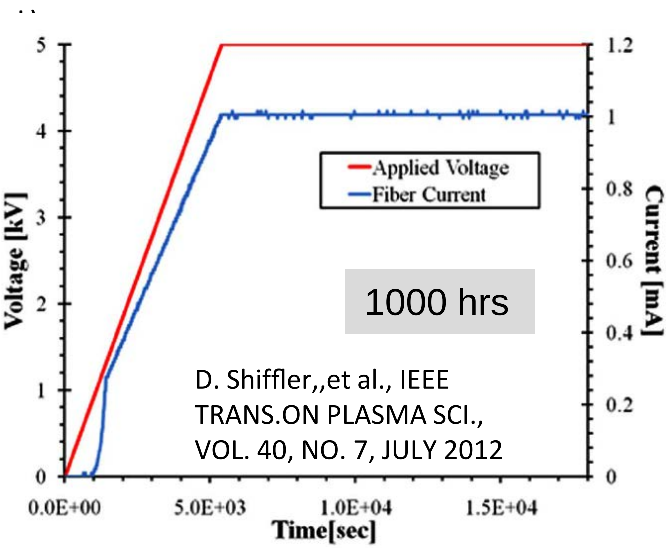
25 hrs @ 200 µA

Degradation due to Joule Heating

CNT Fiber Cathodes







Carbon Nanotube Fiber Synthesis

Two Primary Techniques for Fiber Fabrication

Wet Spinning – CNTs dispersed in superacid then extruded

RICE

Prof. Matteo Pasquali

Strong, Light, Multifunctional Fibers of Carbon Nanotubes with Ultrahigh Conductivity
Science **339**, 182 (2013) N. Behabtu, S. Fairchild, J Ferguson, B. Maruyama, M. Pasquali, et al.,

Dry Spinning w/ Floating Catalyst

UNIVERSITY OF CAMBRIDGE

Prof. Krzysztof Koziol
CNT Fiber Synthesis
Prof. Martin Sparkes
Laser processing

Field emission from laser cut CNT fibers and films
J. Mater. Res., Vol. 29, No. 3, Feb 14, 2014
S.Fairchild, J. Bulmer, M. Sparkes, J. Boeckl, et al

CNT Fiber Fabrication – Floating Catalyst

The carbon nanotube fibre reactor
Department of Materials, Cambridge, UK

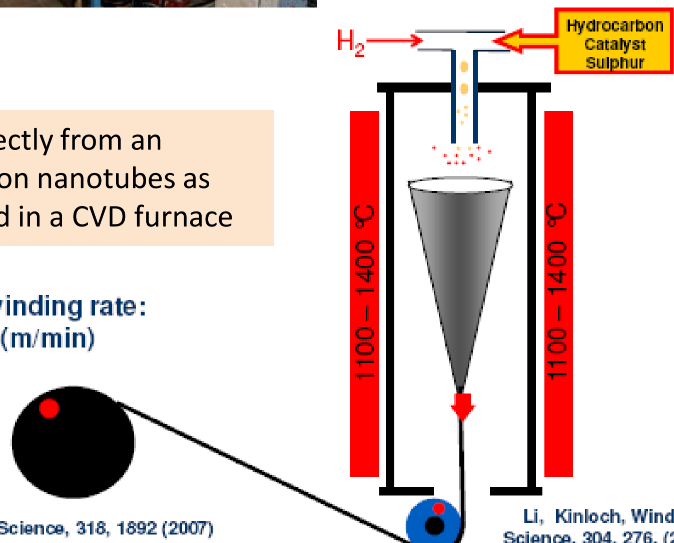
UNIVERSITY OF CAMBRIDGE

Prof. Krzysztof Koziol

Air Force Funded graduate student
- John Bulmer

Fibers spun directly from an aerogel of carbon nanotubes as they are formed in a CVD furnace

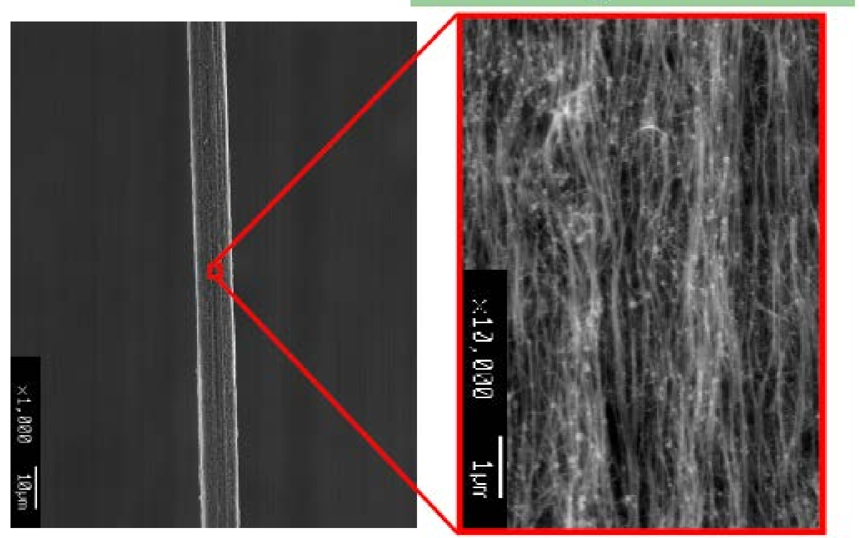
Fibre winding rate:
5 - 100 (m/min)



Koziol et al, Science, 318, 1892 (2007)

Li, Kinloch, Windle, Science, 304, 276, (2004)

Nanotubes aligned with fibre axis



Made with long CNTs (~1mm)
Fiber pulled directly out of reactor

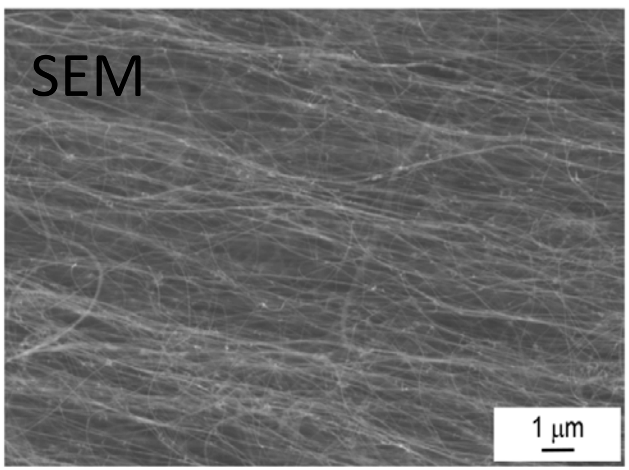
*Koziol et al.Chem. Mater., Vol. 22, No. 17, 2010

AFRL

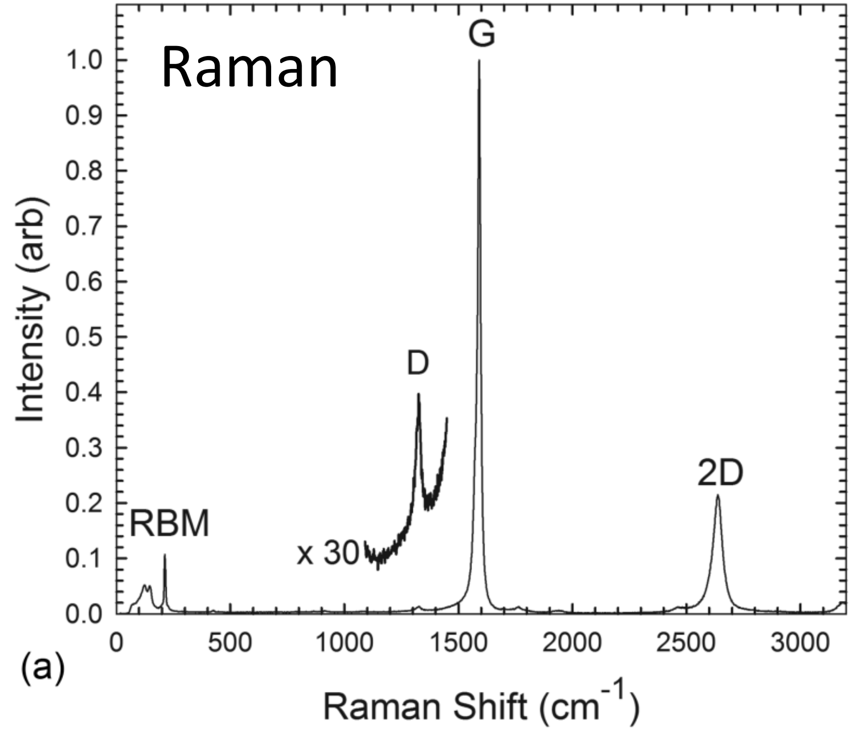
CNT Material

Fabrication

- Floating catalyst CVD Reactor
- Toluene/Ferrocene
- 1200 ^{o}C
- Aerogel cloud
- Mechanically drawn directly from reactor
- Spooled into sheets
- Or Acetone spray condensed into fiber



High degree of bundle alignment



G/D ratio ~19/1

- High degree of graphitic order

RBM 150 cm^{-1}

- Single Walled NanoTubes

Laser Processing of CNT Fiber

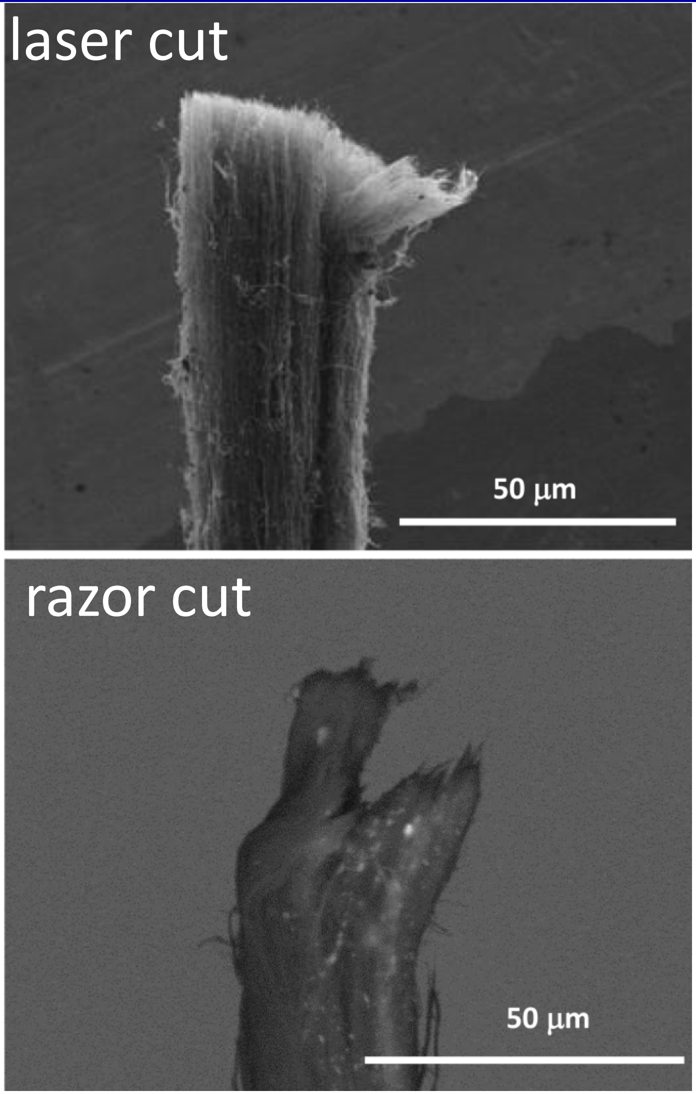
<u>CNT Material Laser Machining</u>

M. Sparks, F. Orozco
University of Cambridge
Institute for Manufacturing
Center for Industrial Photonics

- **SPI Lasers**
  Model G3
  ns
  λ= 1064 nm
  25 kHz

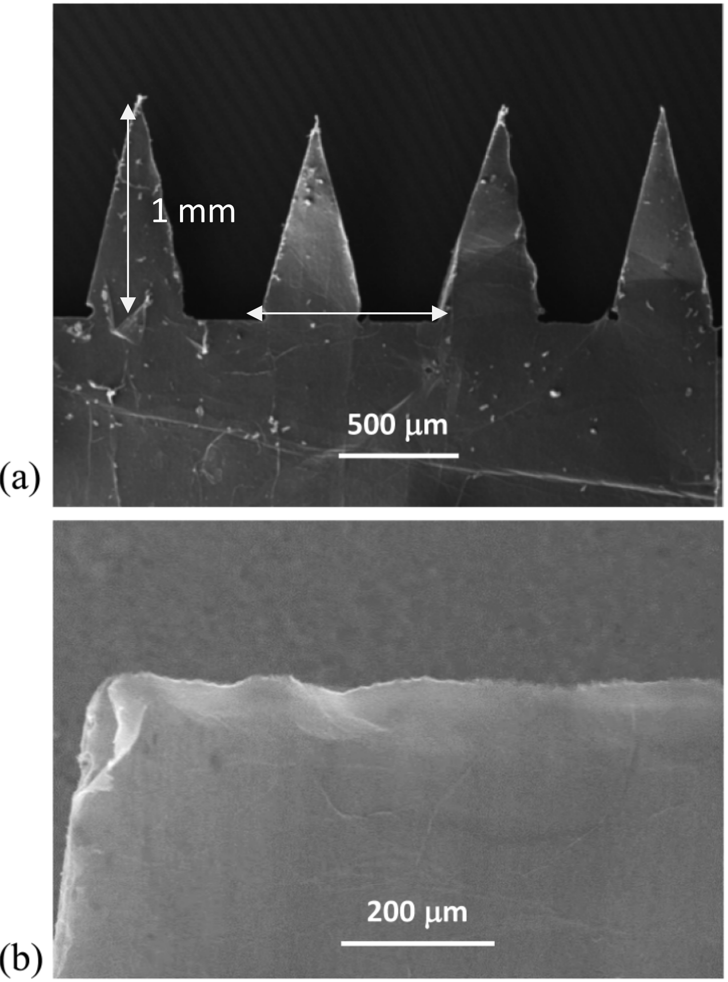
- **Spectra Physics**
  Model Hurricane I
  fs
  λ=800 nm
  5 kHz

(a)



(b)

Laser Cut CNT Sheets

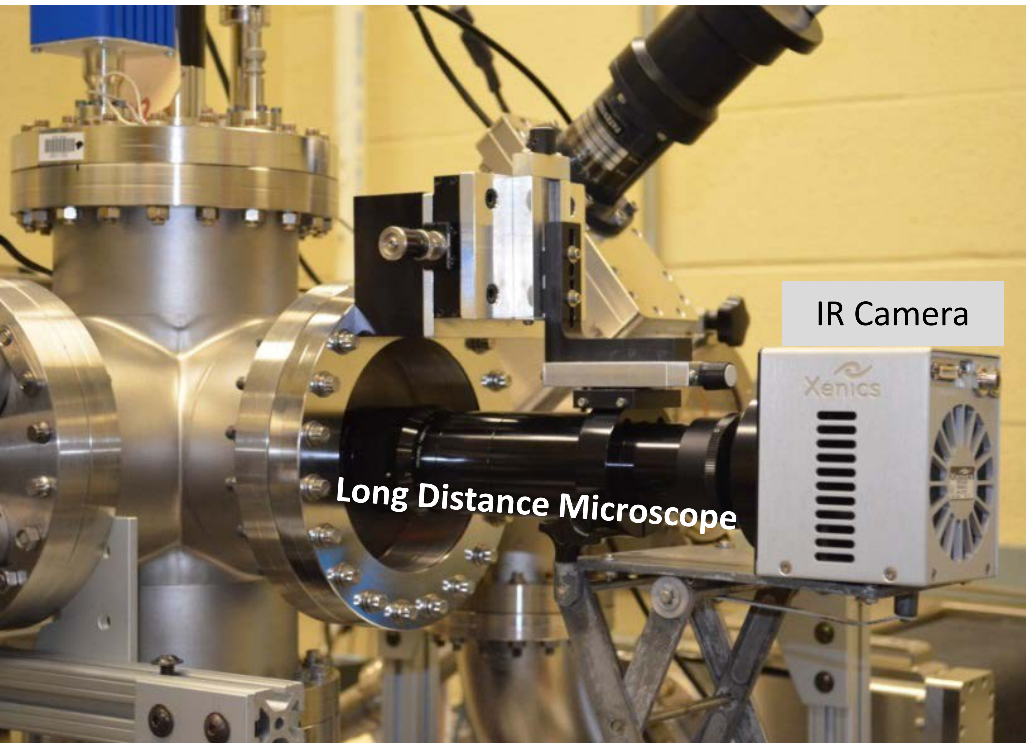


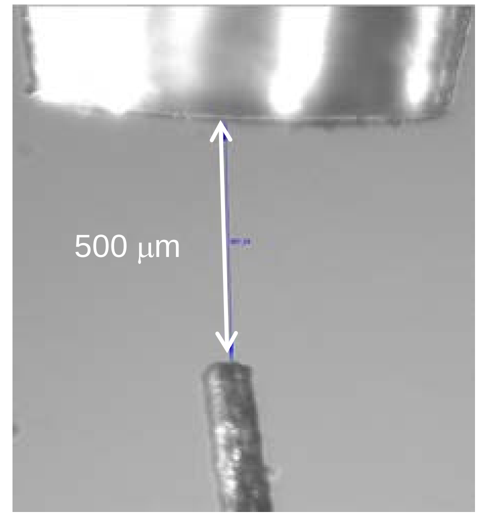
Triangular Pattern for Field Enhancement

- 1 mm x 0.5 mm triangles separated by 0.5 mm
- 1 to 1 height to spacing ratio to prevent e-field screening
- Straight Cut with laser for comparison

Field Emission System

AFRL

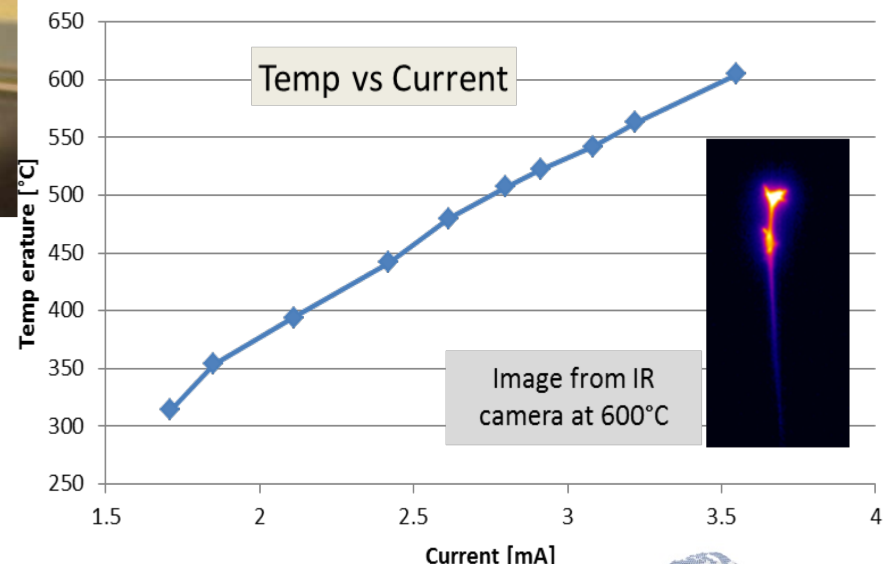




Optical image of gap distance

Voltage ramp – 1-1000 V
1 V per 10 sec

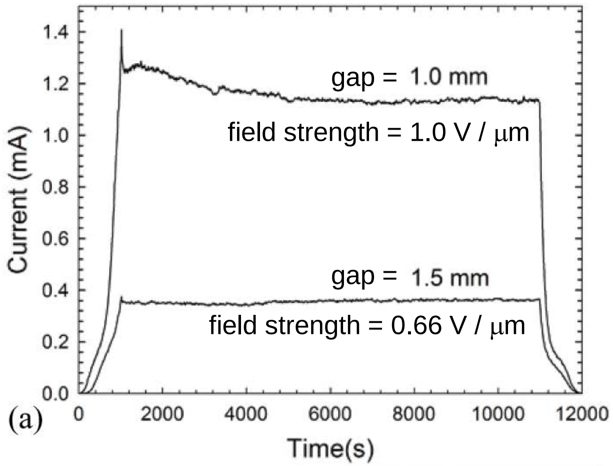
- Optical and IR Imaging
- Residual Gas Analysis (RGA) during FE



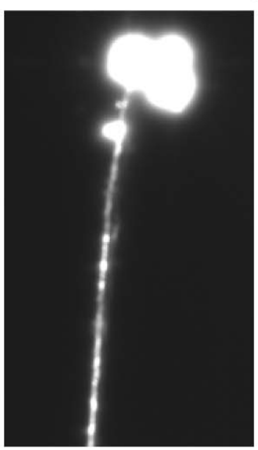
Field Emission

High current at low field strength and long lifetime

laser cut fiber

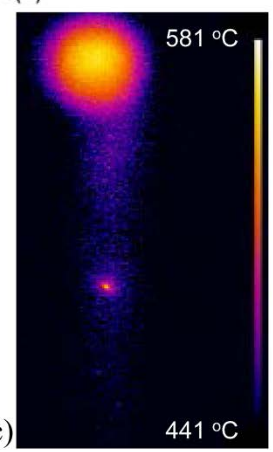


(b)



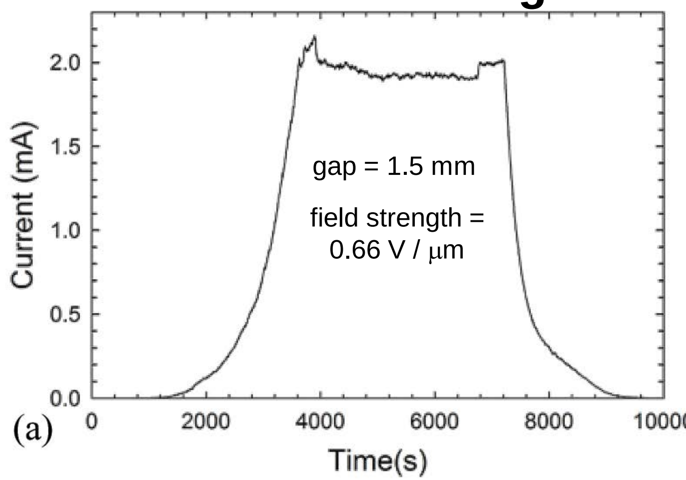
Optical

(c)

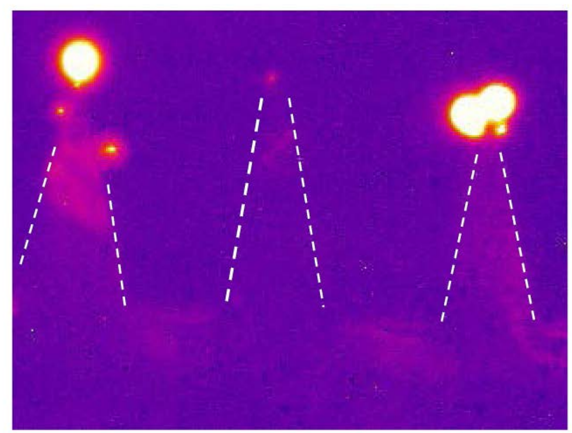


IR

laser cut triangles

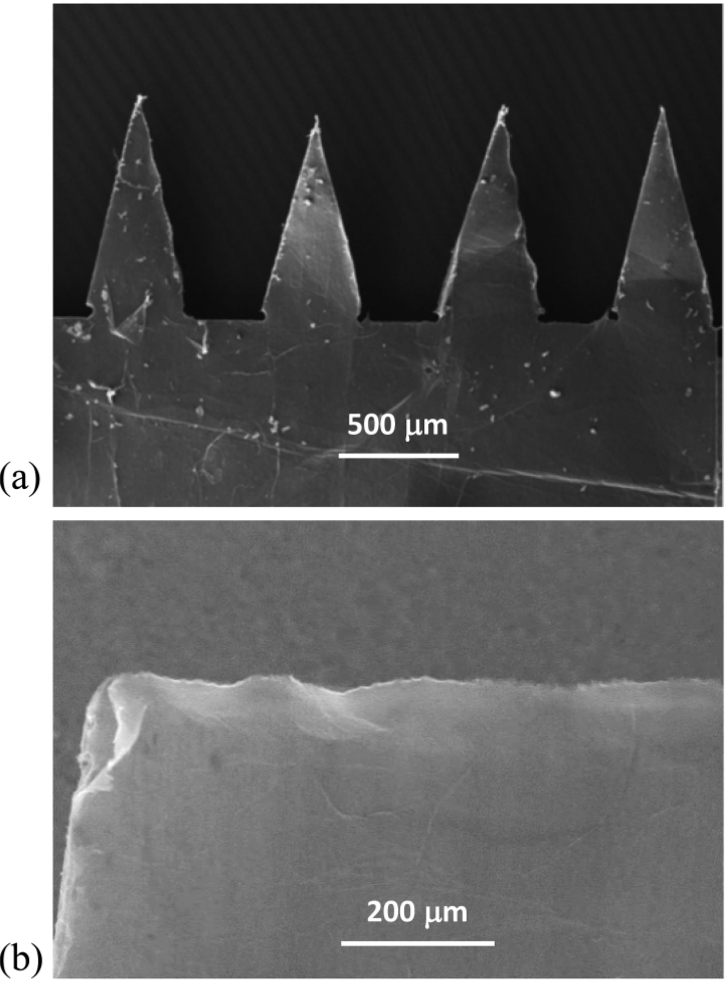


(b)

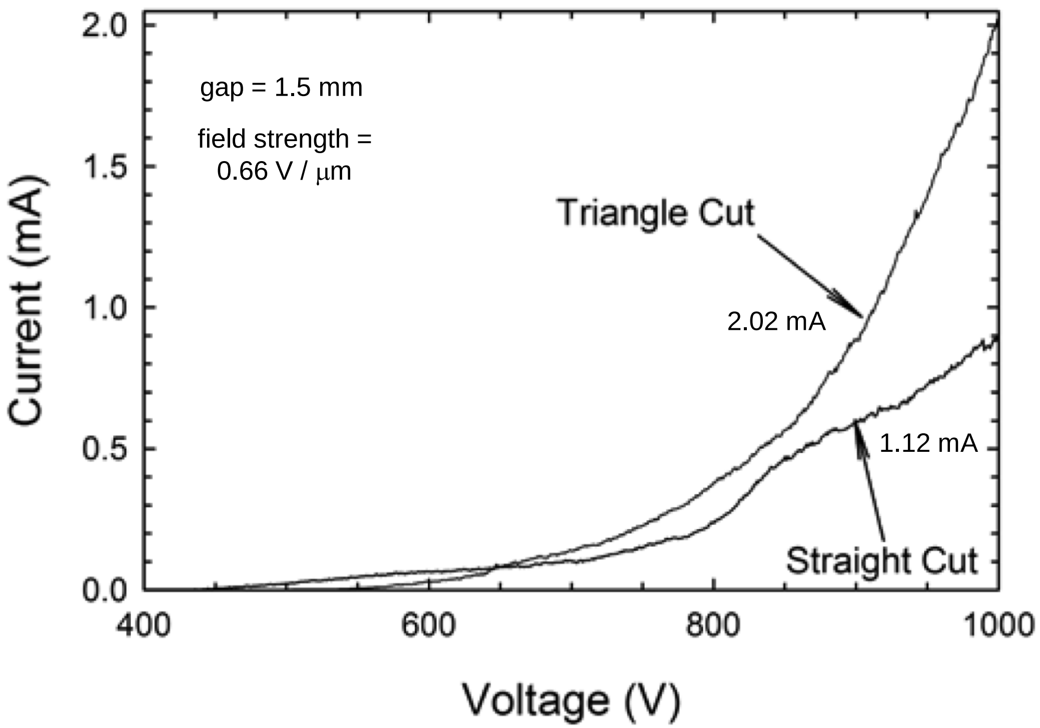


IR

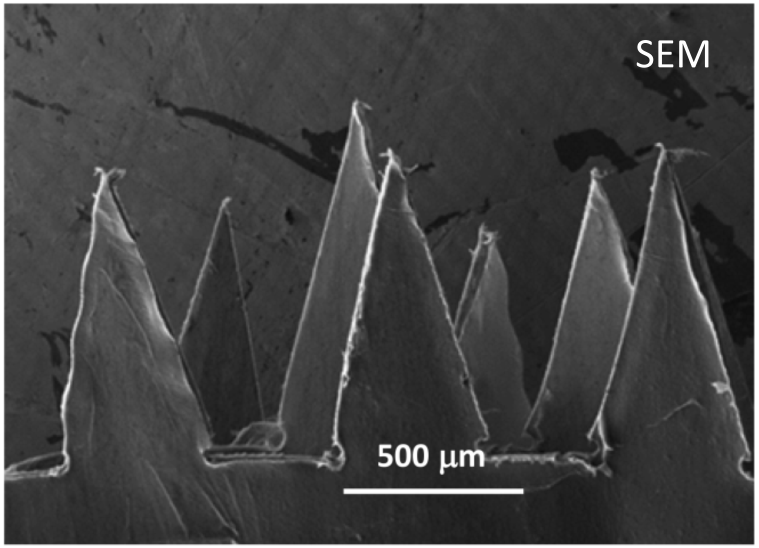
Effect of Laser Pattern



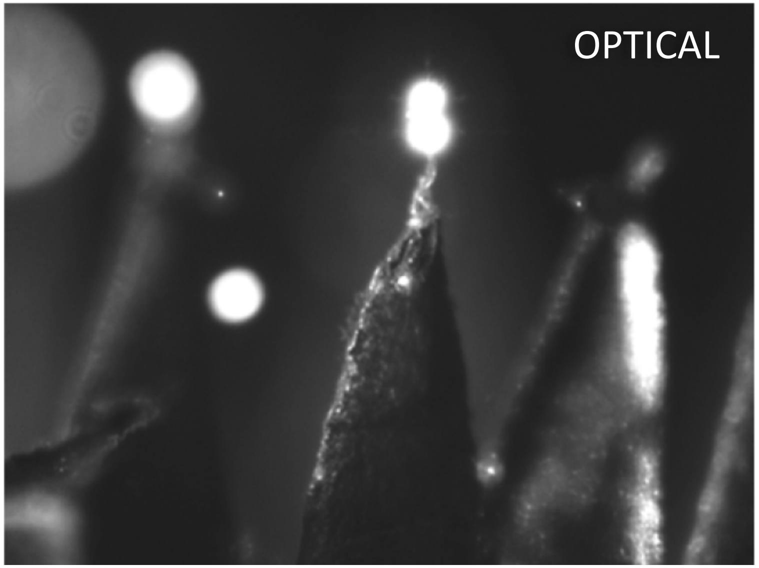
Triangle cut
Compared to straight cut



Multiple Triangle Cut Sheets

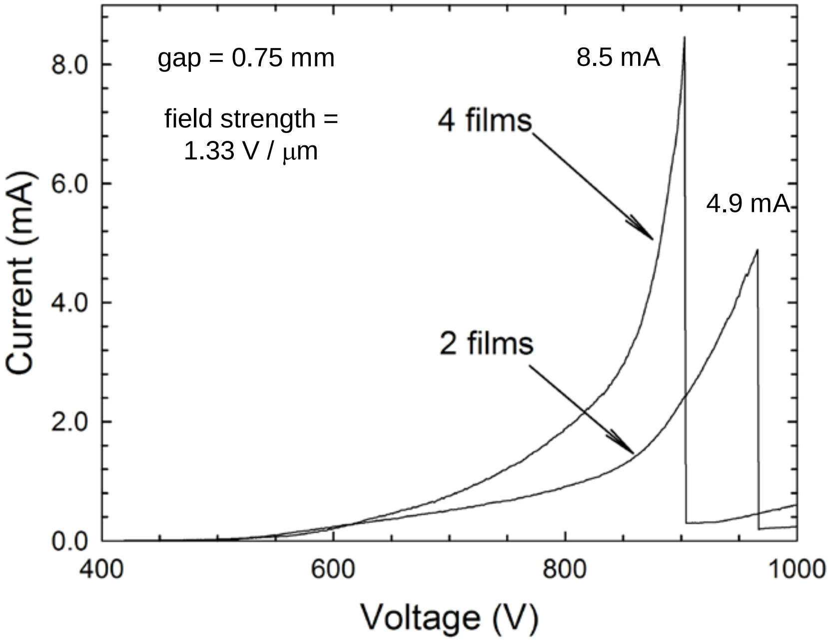


(a)



(b)

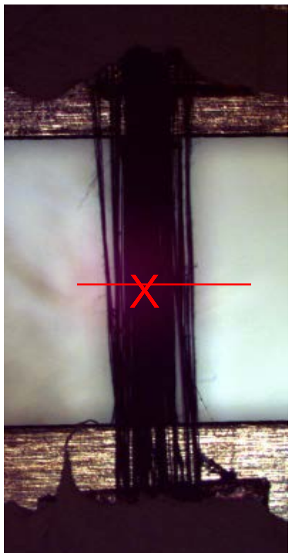
Maximum current vs # sheets



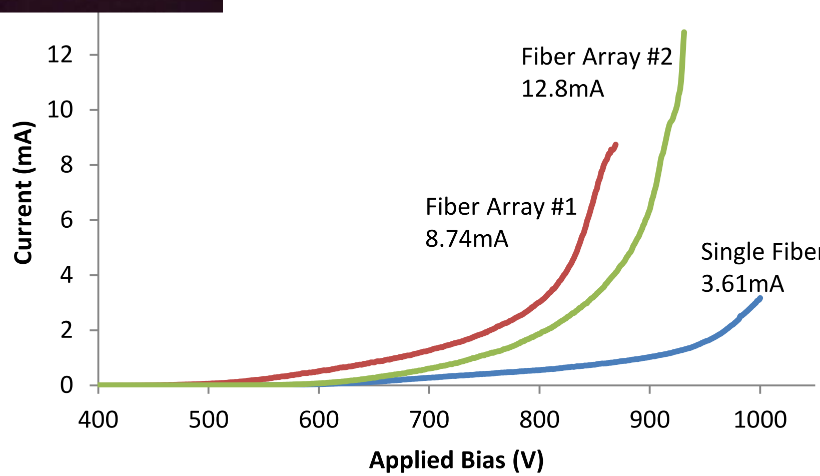
8.5 mA for 1.33 V/µm

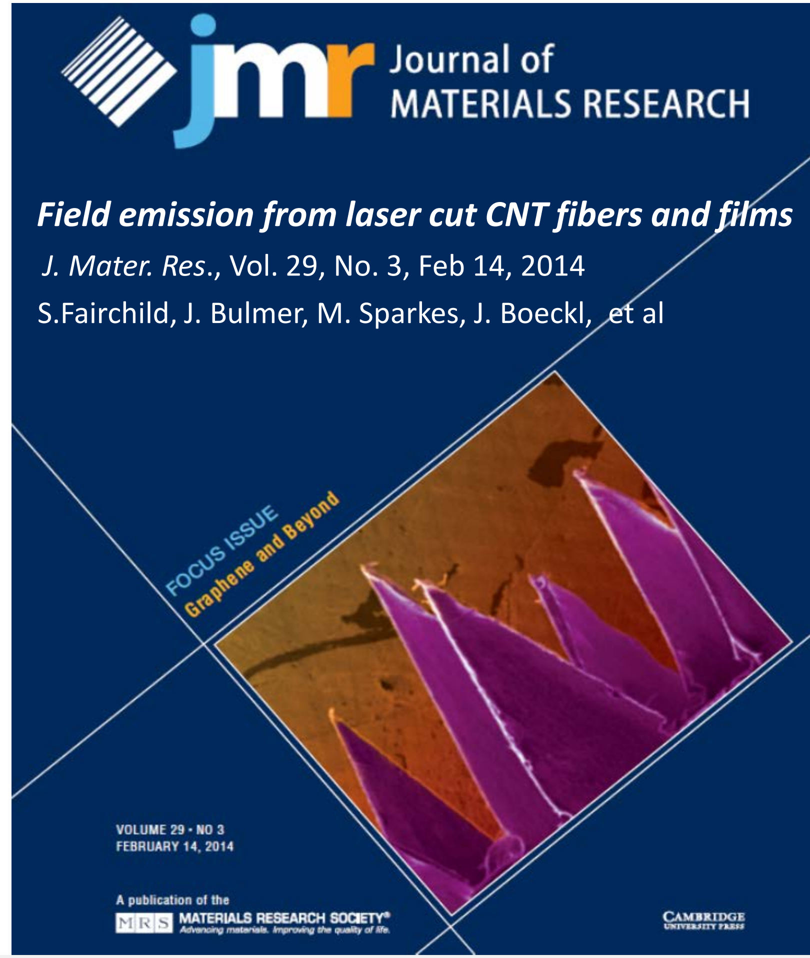
Scale Up to Large Area Cathodes

Make CNT Fiber Array



CNT Fiber Brush

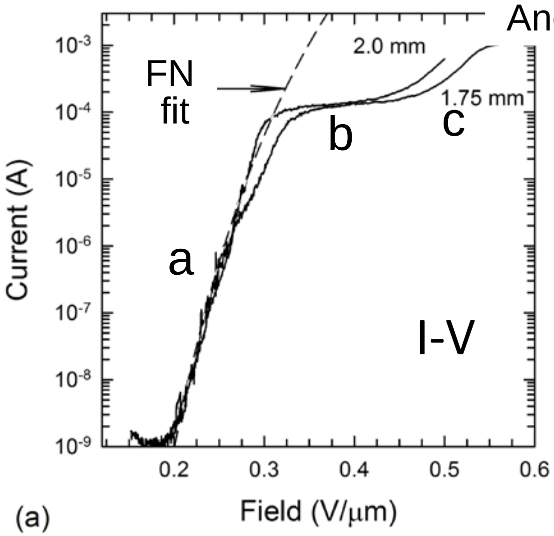




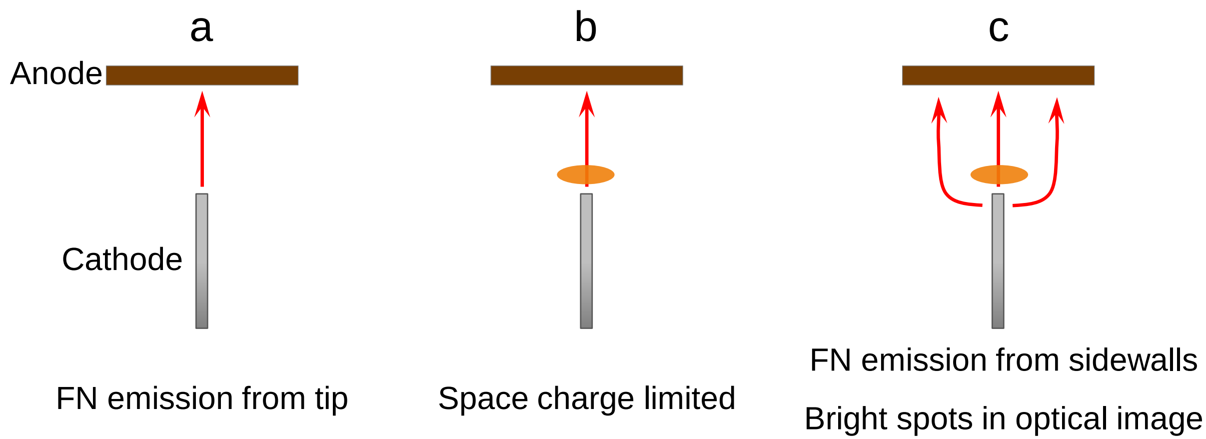
EOARD – Research grant with U of Cambridge, Prof. Kzysztof Koziol & UF laser processing group

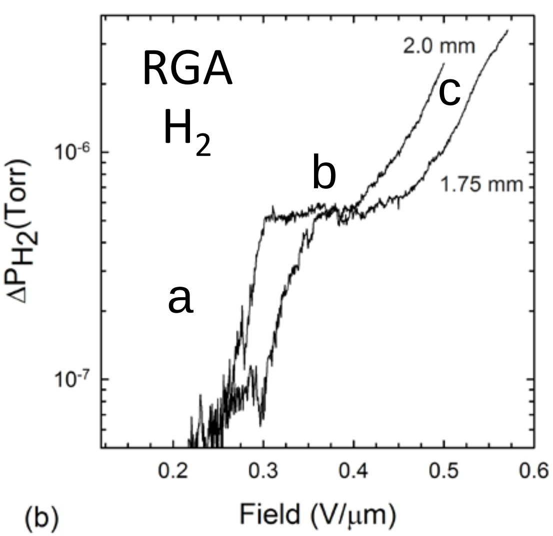
Laser Cut Fiber

Anode-cathode gap distances



<u>Operating Regimes</u>





- Exceptionally low turn on field (~ 0.2 V/μm for 1 μA)
- Well described by Fowler-Nordheim theory at low field
- 3 different operating regimes
- Beyond 0.3V/μm the I-E curve flattens out due to space charge limited flow

Fowler- Nordheim

$$I(Amps) = A_{eff}\frac{1.54 \cdot 10^{-6}}{\emptyset}\beta^2 E_{ext}^2 e^{-\frac{6.83 \cdot 10^7 \varphi^{3/2}}{\beta E_{ext}}}$$

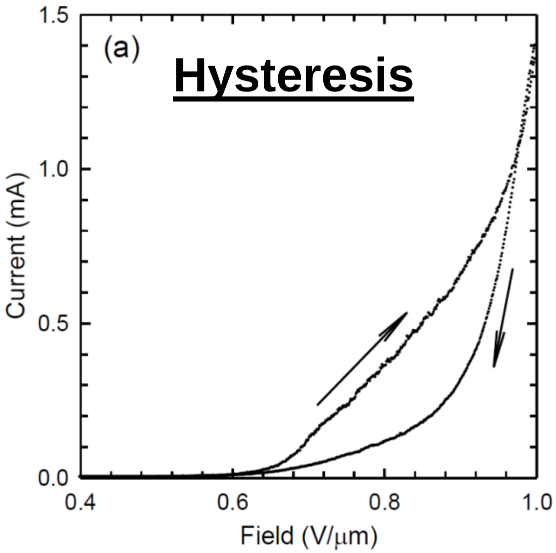
S.B. Fairchild, et al., J. Mater. Res. **29**(3), 392-402(2014)

Summary

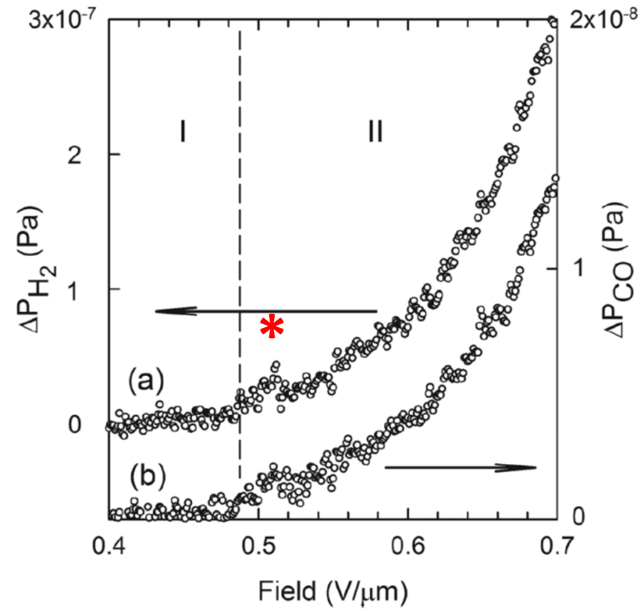
CNT Fiber and Sheet Cathodes

- High current, Low turn on field strengths
- Robust performance with triangle cut sheets
  - (8.5 mA < 2V/μm
- 3 different operational regimes (fiber)
  - Tip emission (FN)
  - Space charge regime (tip)
  - Side wall emission
- Observe H_2, CO, & CO_2 desorption accompanying FE
  - $\Delta P_{H_2} > \Delta P_{CO} > \Delta P_{CO_2}$
  - $\Delta P_{H_2O} \sim 0$

Hydrogen in Vacuum Electronic Devices
Cathodes

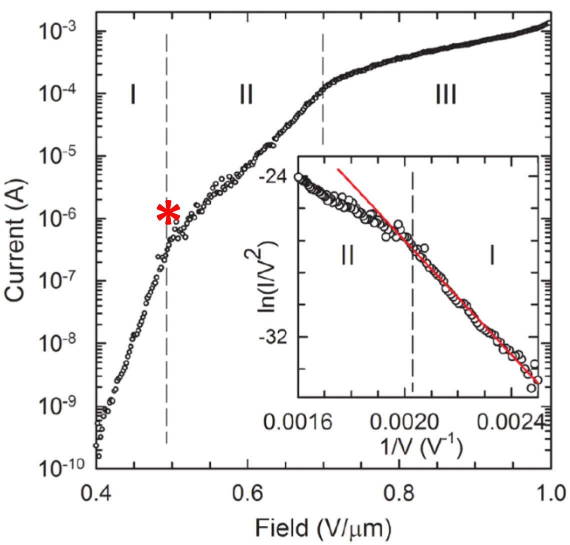


Gas Desorption during Field Emission



FE Regimes

I Adsorbate enhanced
II Transition
III Intrinsic CNT emission



Breakpoint between Regions I & II

- Coincides with H_2,CO,& CO_2 desorption thresholds
- H_2, CO & CO_2 desorption at same threshold field strength
- $\Delta P_{H_2} > \Delta P_{CO} > \Delta P_{CO_2}$
- $\Delta P_{H_2O} \sim 0$

P. T. Murray, T. C. Back, M. M. Cahay, S. B. Fairchild, B. Maruyama, N. P. Lockwood, & M. Pasquali, Appl. Phys. Lett. **103**, 053113 (2013).

Hydrogen in Vacuum Electronic Devices
Anodes

Application- High Power Vacuum Electronic Devices

The Problem
Collecting an electron beam results in:

- Secondary electron emission (SEE)
- Electron Stimulated Desorption (H_2)

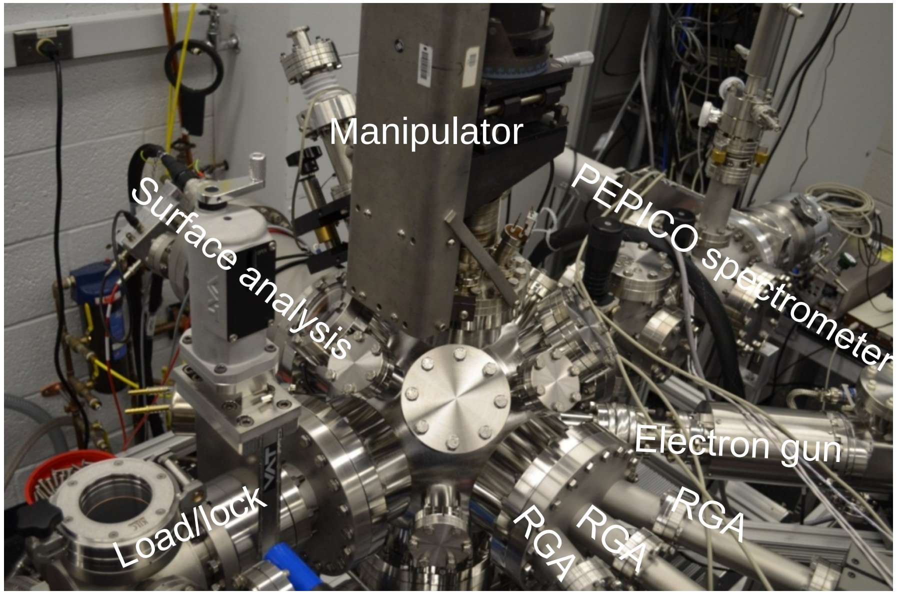
Result
Electron multipacting, limiting device power

- Secondary electron avalanche
- Accelerated by RF field
- Reflects energy into source
- Destroys cavity window

The Need
- Coatings that suppress SEE
- Reduce outgassing of Hydrogen

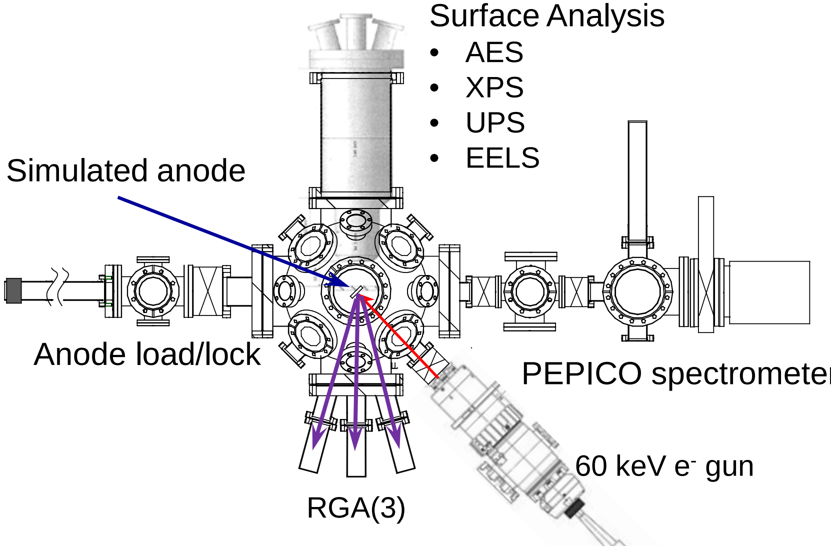
Goals
- Simulate conditions of an operating anode by developing a unique anode materials characterization system
- Explore novel anode coatings, materials and structures.

Anode Materials Characterization System



AMCS

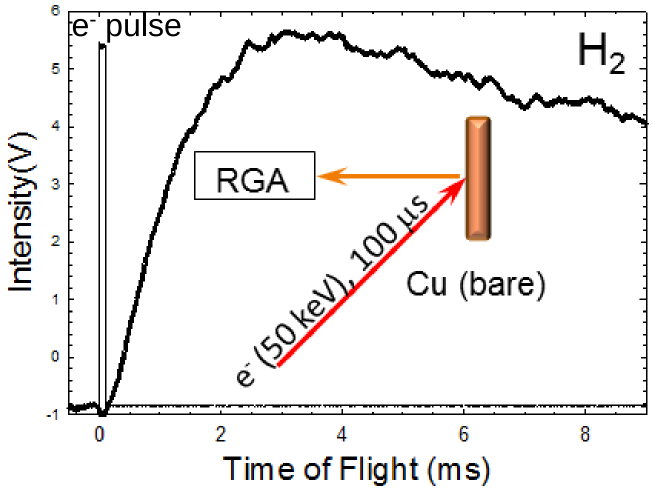
Simulates processes occurring at anode surfaces during e-beam collection

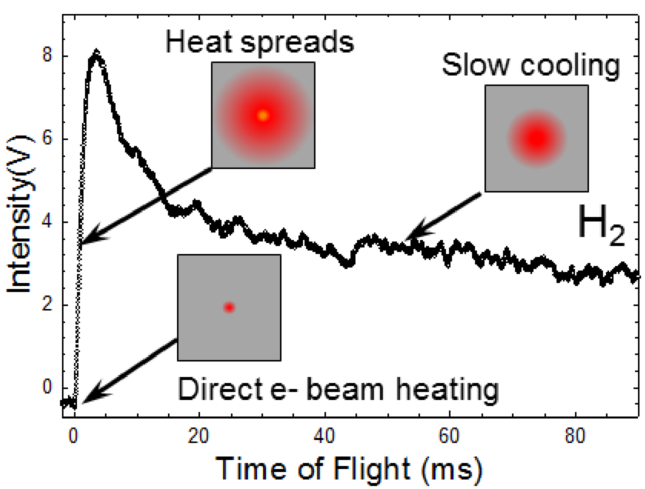


Anode Materials Characterization System

- High energy e$^-$ gun (CW or pulsed)
- Surface characterization of anodes (Before & after e$^-$ bombardment)
- Measure TOF distribution of desorbed species (H_2, CO) (Desorption mechanism, Translational temperature)
- Photoelectron-photoion coincidence (PEPICO) spectrometer (Vibrational state distribution of desorbed species)

Time of Flight Results

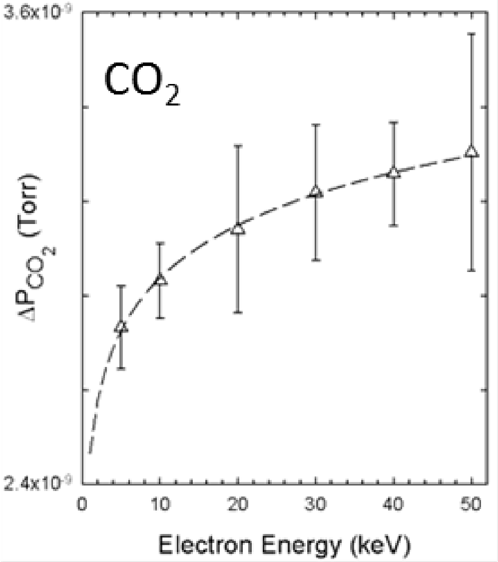


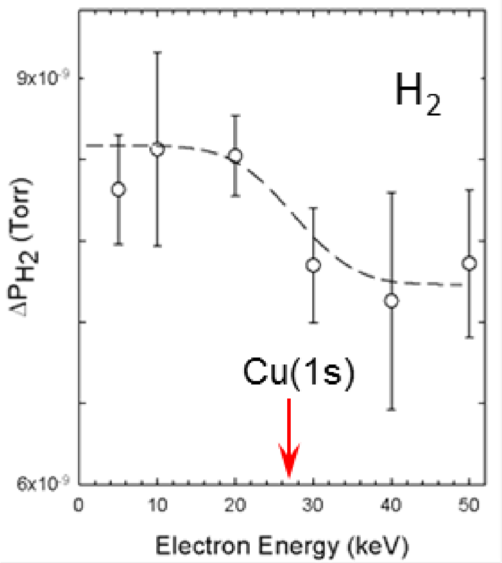


- No evidence of prompt (electronically induced) desorption)
  - Desorption timescale on the order of 10's of ms
- Thermally induced desorption
  - Heat diffusion from bombarded area on target
- Will confirm by time resolved IR imaging.

Desorption Yields

Kinetic energy dependence





<u>Cu target</u>

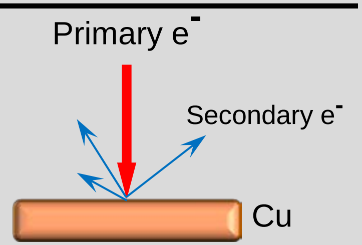
- CO_2 yield monotonically increases with electron KE
  - More power into target = more desorption

- H_2 inflection near Cu(1s) ionization threshold
  - Is X-ray emission a non-thermal energy sink?

- Still to do: measure SEE and dependence on e^- KE

Novel Anode Development

Current Anode SOA

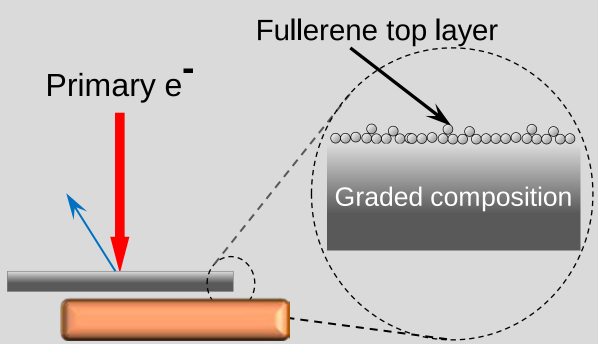


Goal is to reduce

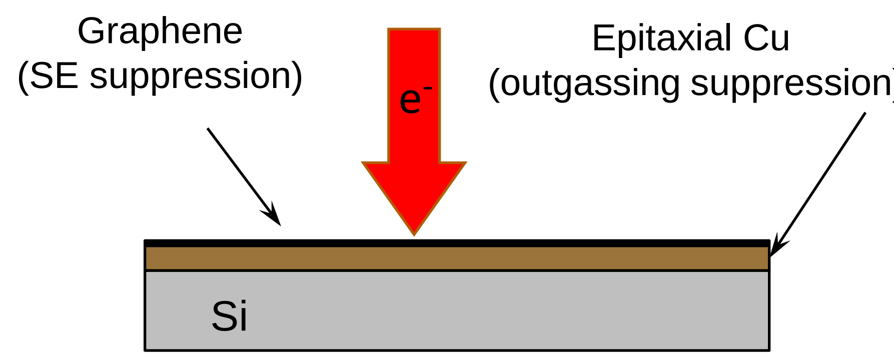
- Secondary Electrons
- Desorbed Gas

Proposed

Add electron absorbing layer



Reduce secondary electron yield



Ultralow Secondary Electron Emission of Graphene

Jun Luo, Peng Tian, Cheng-Ta Pan, Alexander W. Robertson, Jamie H. Warner, Ernie W. Hill, and G. Andrew D. Briggs

VOL. 5 ▪ NO. 2 ▪ 1047–1055 ▪ 2011 ACSNANO www.acsnano.org

Other Materials of Interest:

Directionally solidified eutectics

Cu/Ti solid solutions

Conclusions

- Observe H_2, CO, & CO_2 desorption from Cu surfaces
- No significant H_2O desorption observed
- H_2,CO, &CO_2 desorption are thermally driven

  - Will confirm soon by time-resolved IR imaging
- H_2 and CO desorption yields are different
- CO_2 yield monotonically increases with electron KE
- H_2 inflection near Cu(1s) threshold

  - Is X-ray emission a non-thermal energy sink?

Future Work

- Cathodes
  - Scale up fiber arrays
  - Develop robust coatings
- Anode Materials
  - Develop multi-functional materials
    - High electrical conductivity
    - Low outgassing and secondary electron yield

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Dr. John Luginsland, Dr. Jason Marshall

Dr. Ali Sayir

Fin!