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PLANAR CARBON NANOTUBE NETWORKS:
HIGHLY CONDUCTIVE, FLEXIBLE & TRANSPARENT ELECTRODES, FIELD EMITTERS & INFRA-RED SENSORS

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OUTLINE

1) Motivation

2) Flexible, transparent CNT film conductors

Electro-Optical Characterisation

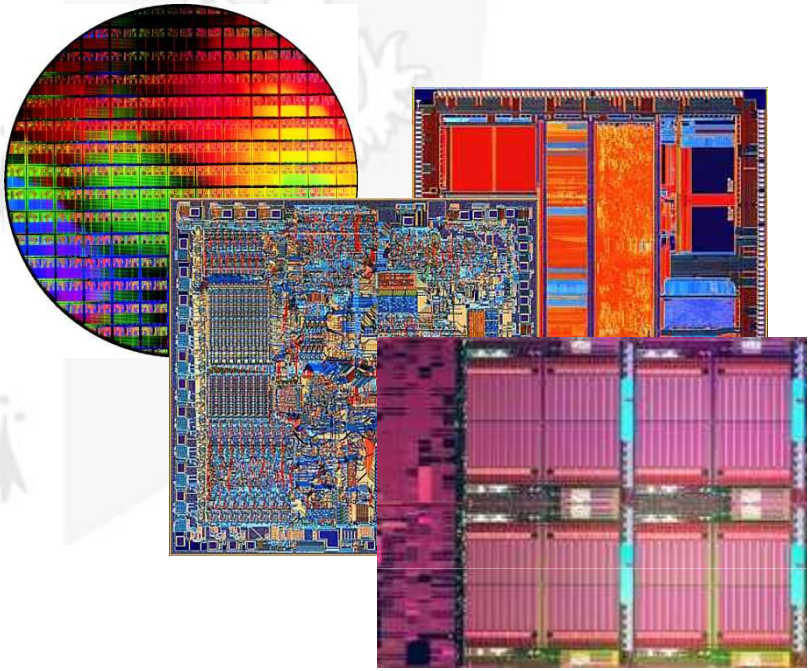
Mechanical Durability

2) CNT Planar Field Emitters

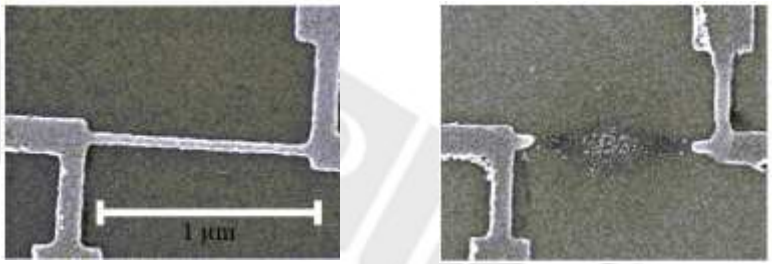
3) Fully Suspended CNT IR Sensor

BUT WHY DO THIS?

TODAY!



One of many problems...



IN THE FUTURE

We want...

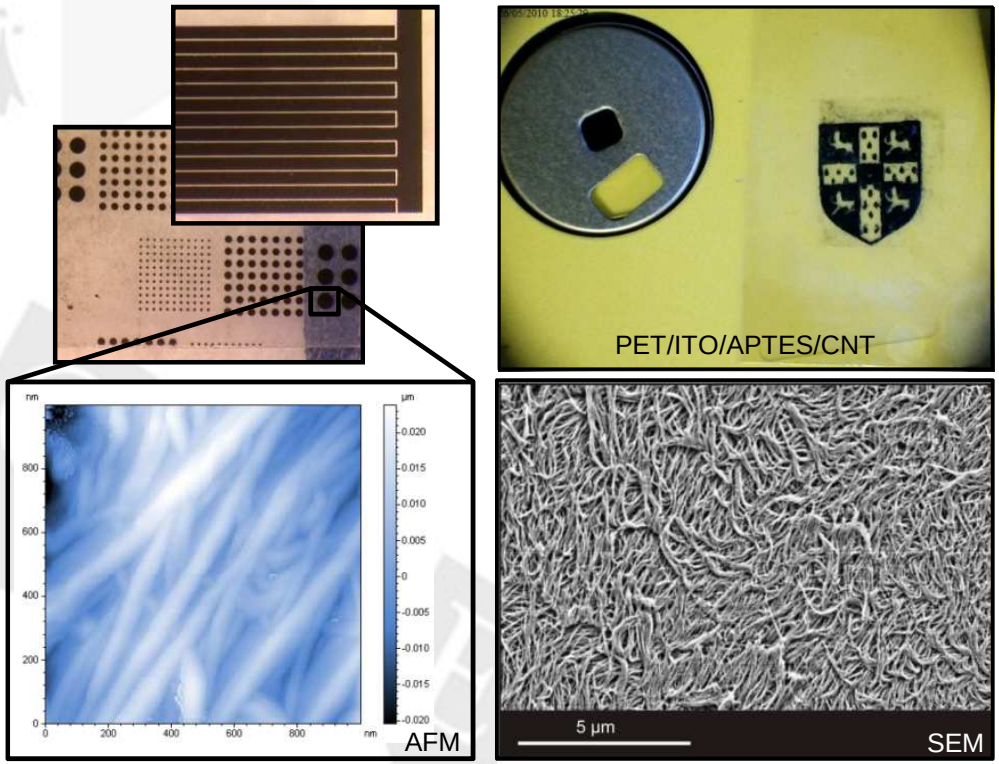
- flexibility
- transparency

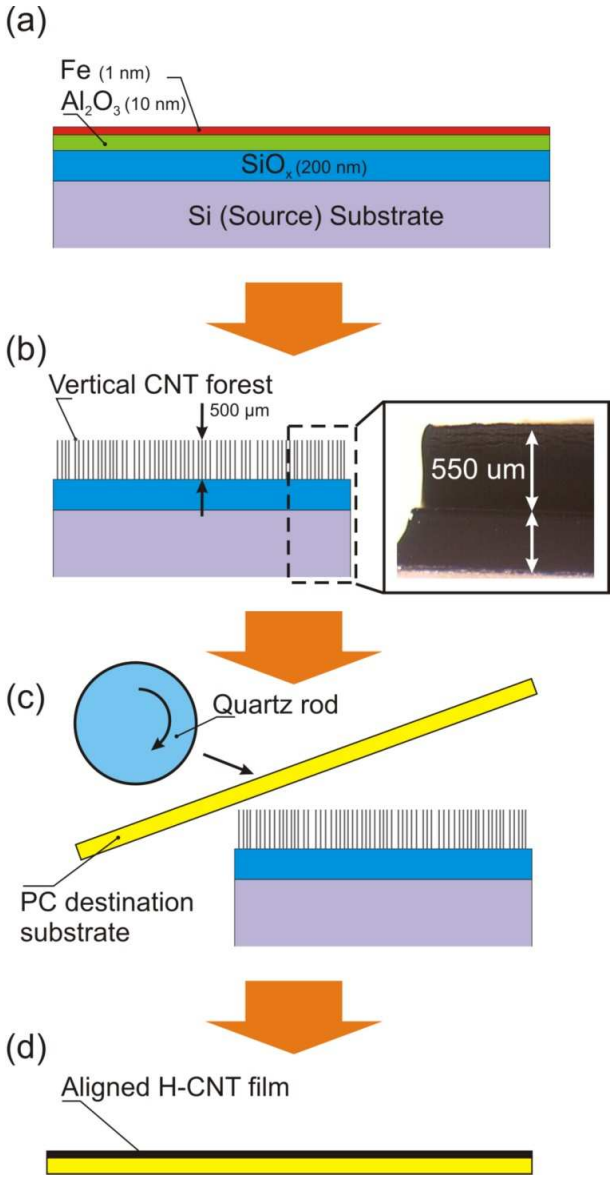
We need...

- high current densities
- bottom-up fabrication

A) FLEXIBLE, TRANSPARENT CNT FILM CONDUCTORS

- Physical, binderless transfer of CNT networks onto PC Substrates
  - ✓ Flexible and Simply patterned (Post growth 0_2 RIE or pre- synthesis catalyst passivation)
  - ✓ Low sheet resistivity (1.2 Ω/□) @ 10% optical transmission
  - ✓ Large active surface mass ~2.3 mg/cm^2 (P. Hiralal, M. Cole, *et al. Nanocarbon 2010, China*)
  - ✓ *Applications.* : interconnects, optoelectronics, supercapacitors, etc.





Electro-Optical Characterisation

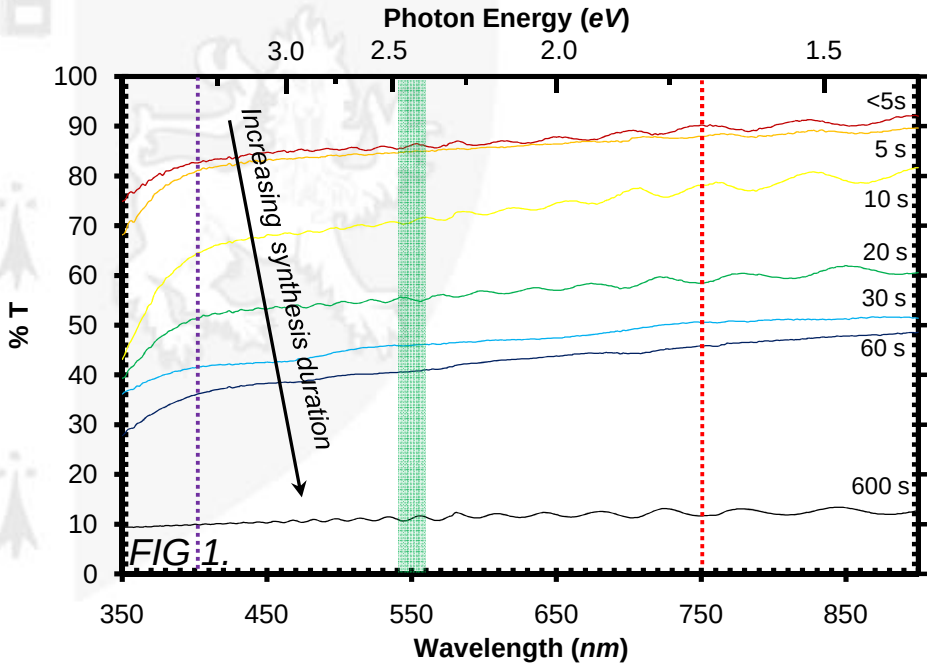
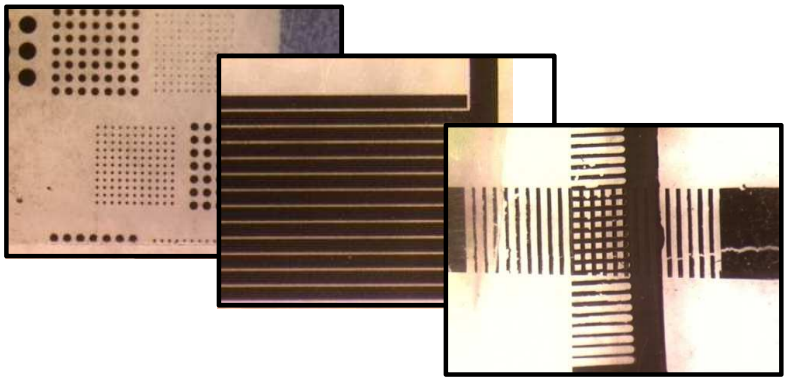
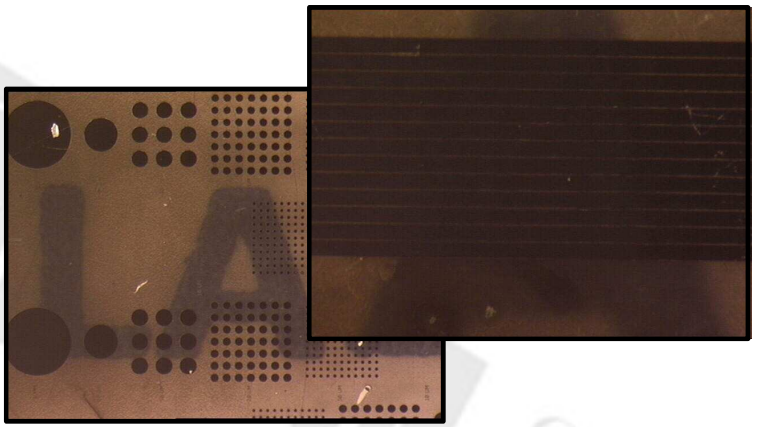


FIG 1.





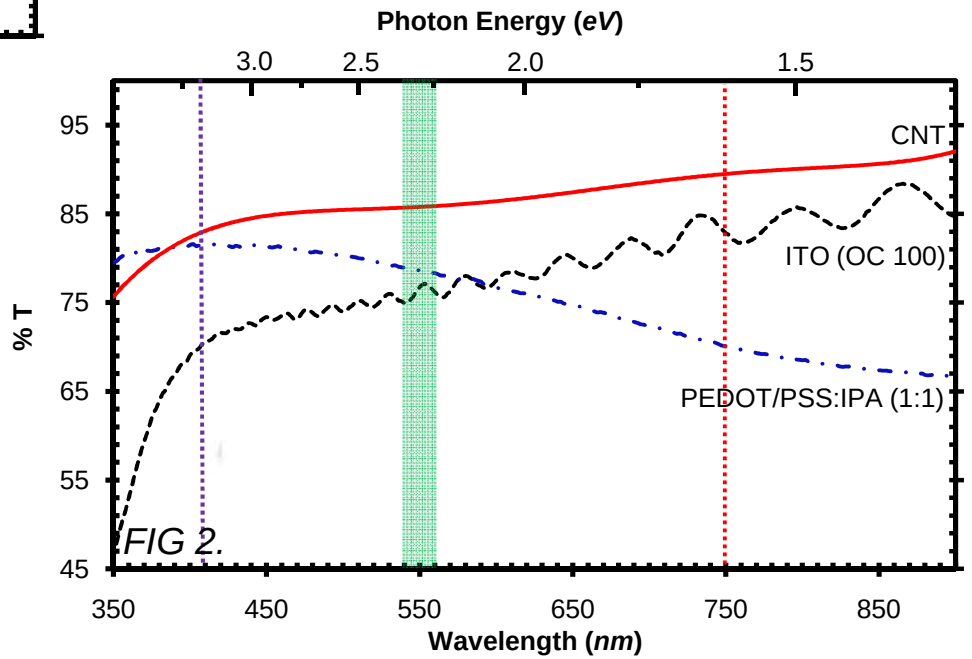
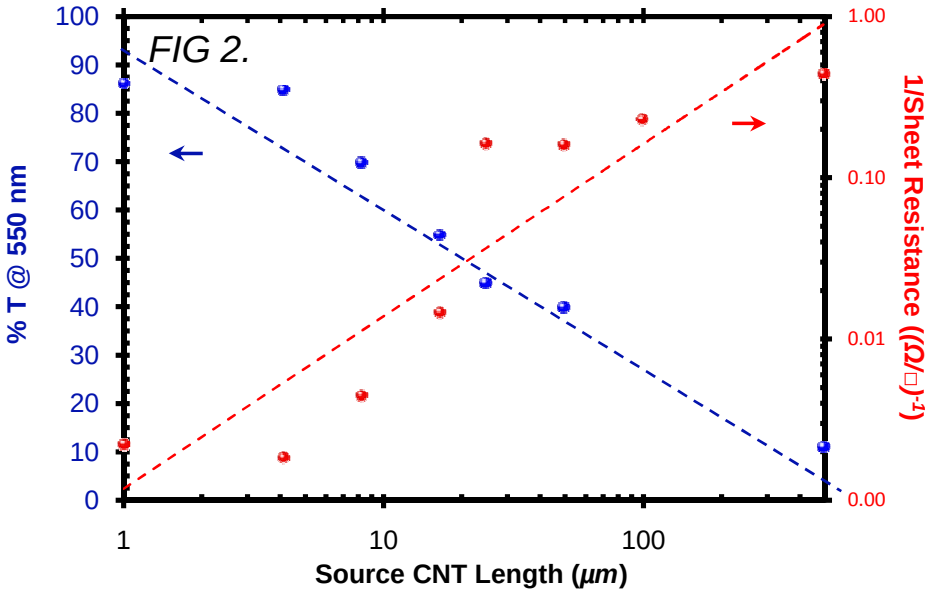


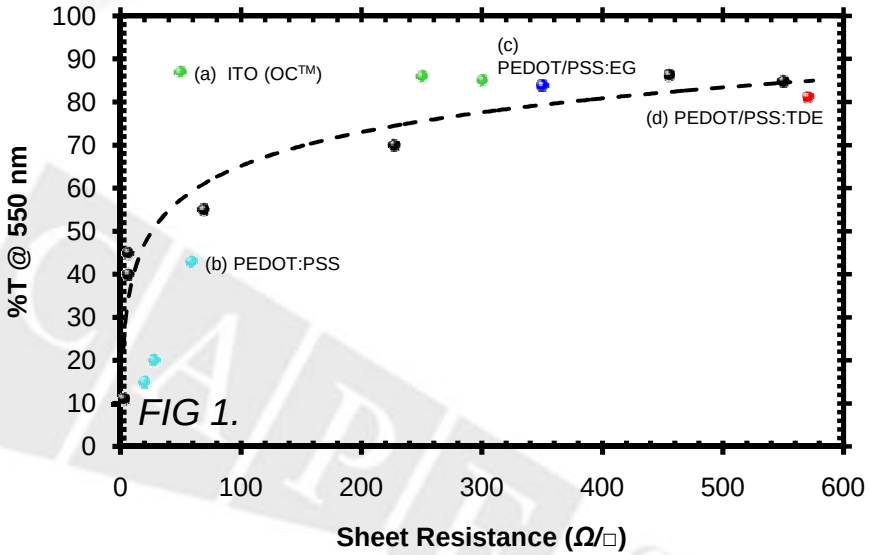
FIG 2.

M. Cole, Y. Zhang, et. al. submitted

Electro-Optical Characterisation

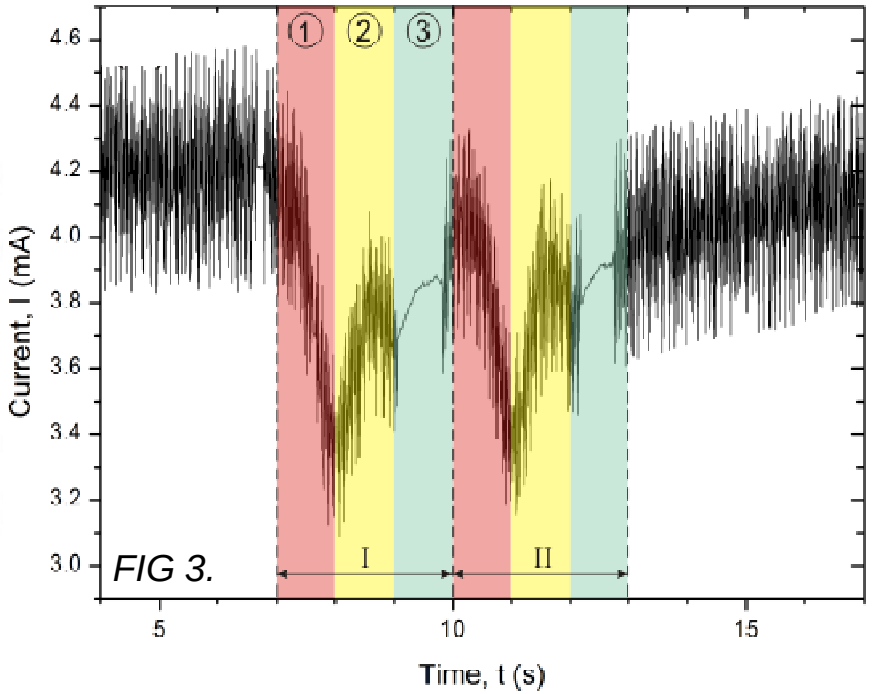
- ✓ Importance of *length* and *packing density* (c. 10^{10} CNTs/cm^2) to inter CNT binding by VdWs interactions
- ✓ Simply tuneable optical and electrical characteristics



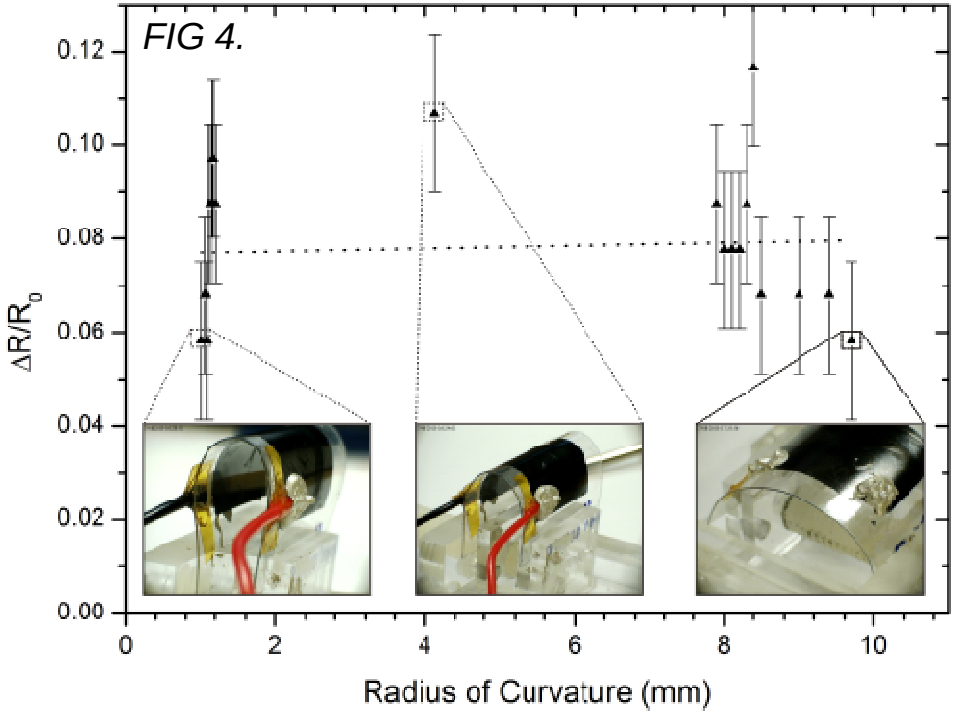


- ✓ Comparable electro-optics to PEDOT:PSS , enhanced PEDOT:PSS and ITO
- ✓ $$T = \left[1 + \frac{Z_0}{2R_s}\left(\frac{\sigma_{opt}}{\sigma_{dc}}\right)\right]^{-2} = \left[1 + 188.5\frac{1}{R_s}\left(\frac{\sigma_{opt}}{\sigma_{dc}}\right)\right]^{-2}$$
- ✓ $$\left(\sigma_{opt} / \sigma_{dc}\right) = 0.178$$

Mechanical Durability



- STRAIN
  - ✓ Highly compressed, self supporting CNT 'paper'
  - ✓ Embedded in RTV Si rubber
  - ✓ ε = 21.8% (not max)
  - ✓ c.f. to: $\varepsilon_{max,ITO}$=1.15%, $\varepsilon_{max,graphene}$ = 15 %



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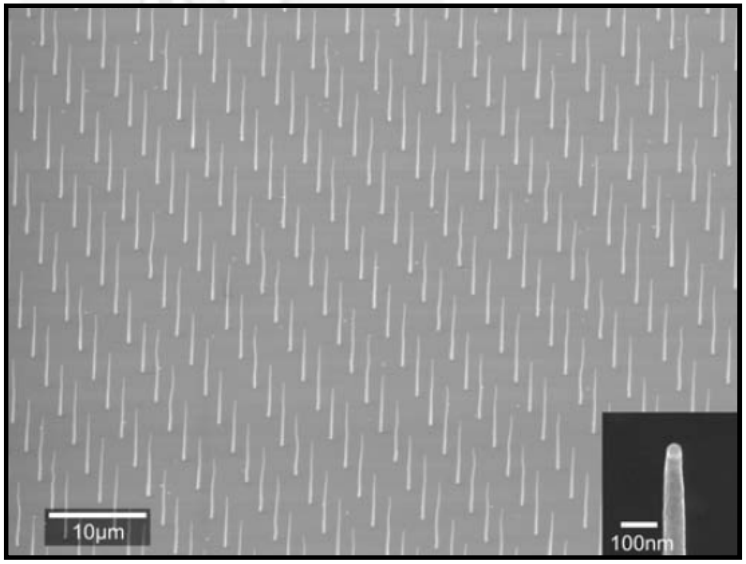
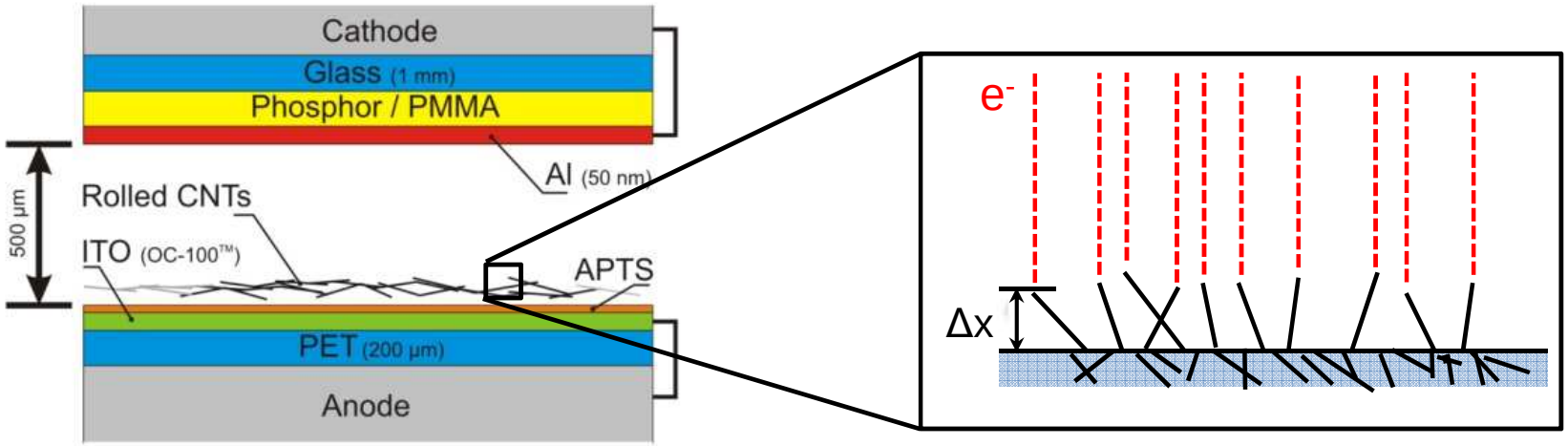
B) FIELD EMISSION & WHY CNTs?

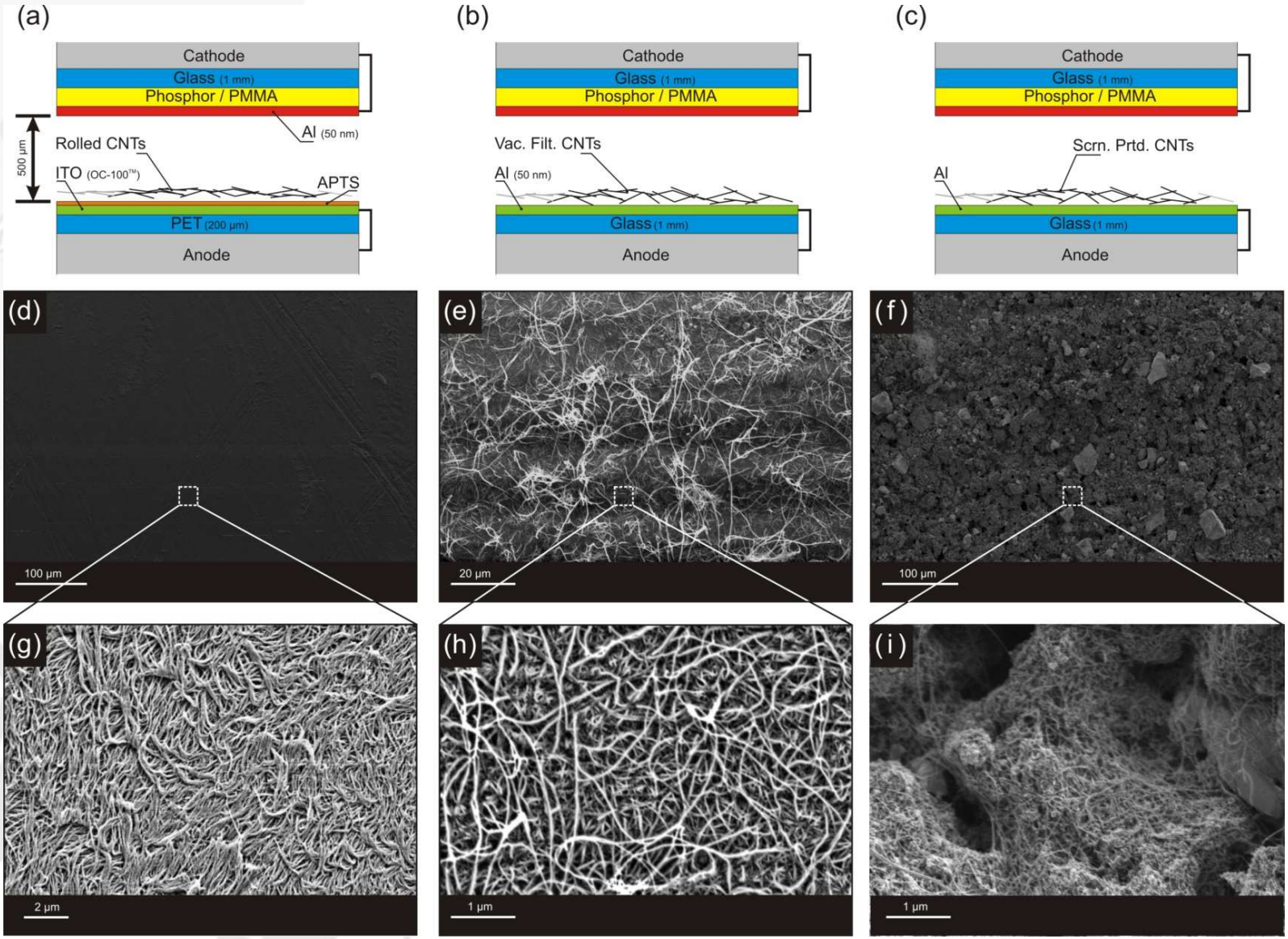


$$J = A\left(\beta^2 E^2/\phi\right)\exp\left(-B\phi^{3/2}/\beta E\right)$$



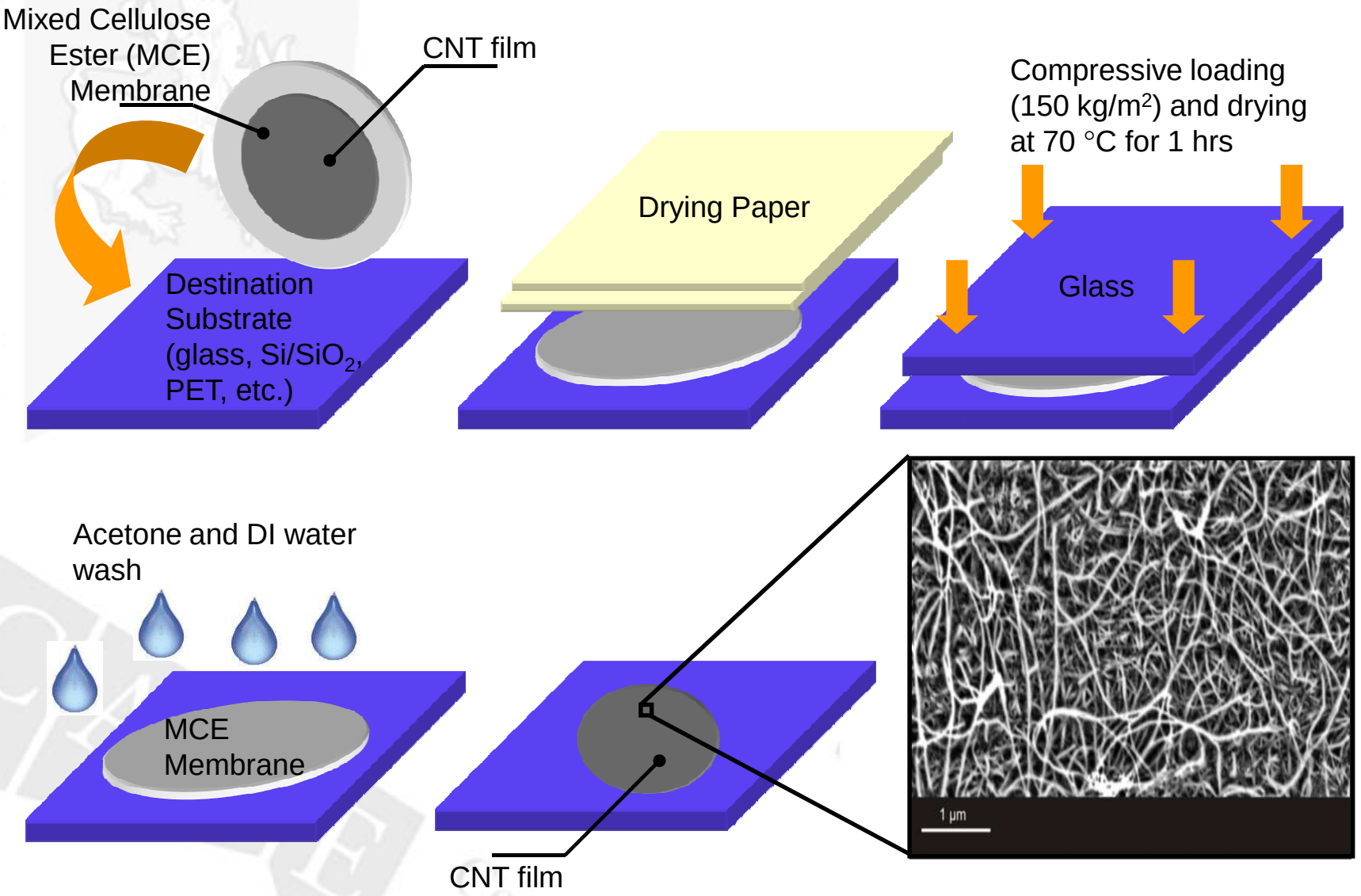
*K. B. K. Teo, et al., APL **79** (2001) 1534*

B) PLANAR CNT FIELD EMITTERS



M. Cole, C. Li, et. al. submitted

B) PLANAR CNT FIELD EMITTERS



*Wu et. al. Science **305** (2005) 1273*

B) PLANAR CNT FIELD EMITTERS

- ✓ Consistently low turn on field (<1.5 V/µm) throughout
- ✓ Thresh. field/Emission Current
  1.15 V/µm / 2.88 mA (roll.)
  1.30 V/µm / 1.48 mA (scr. prntd.)
  1.40 V/µm / 1.38 mA (vac. filtd.)
- ✓ Enhancment, β (α aspect ratio)
  66.2 (roll.)
  29.0 (vac. Filtd.)
  1.6 (scr. Prntd.)

- ✓ Low sheet resistance → electrodeless field emitters
- ✓ Scrn. Printed: High impurity content in commercial CNT paste adds a ballast resistance
  - Increases uniformity
  - BUT reduced current density / brightness

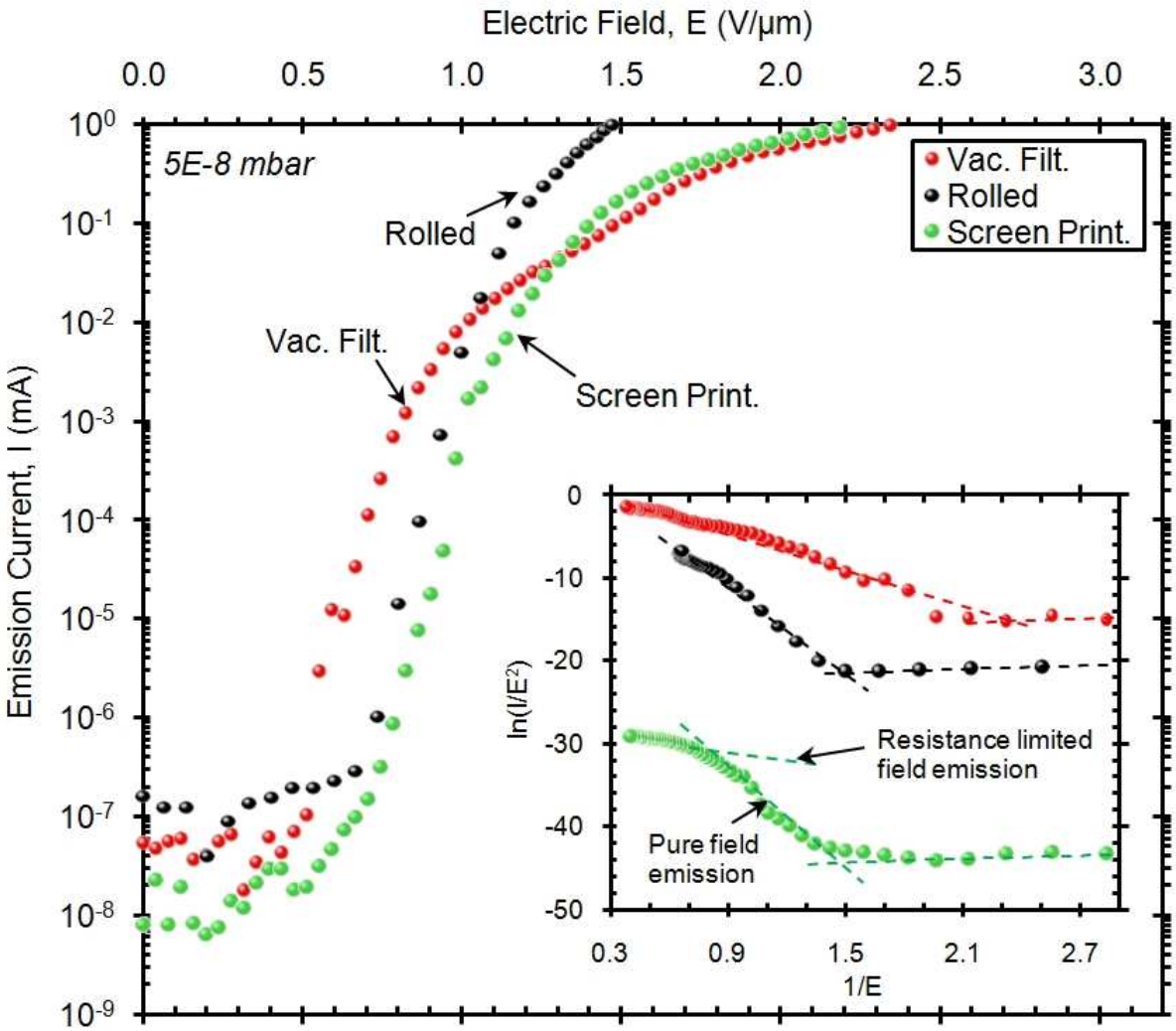


FIG 6.

M. Cole, C. Li, et. al. submitted

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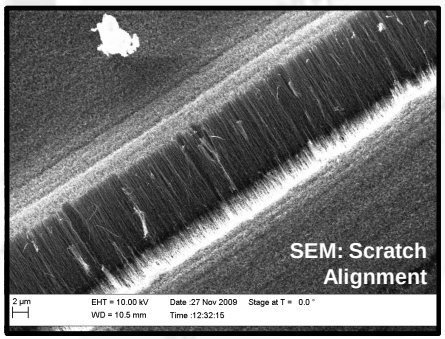
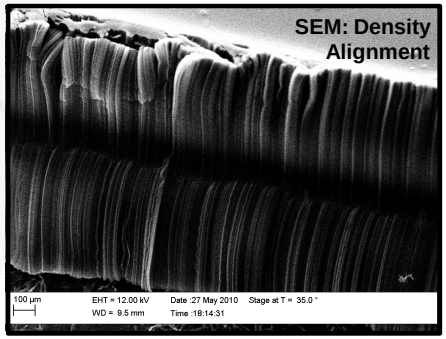
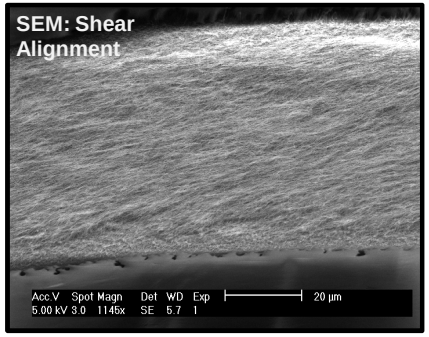
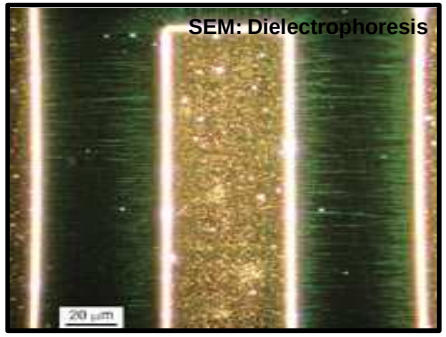
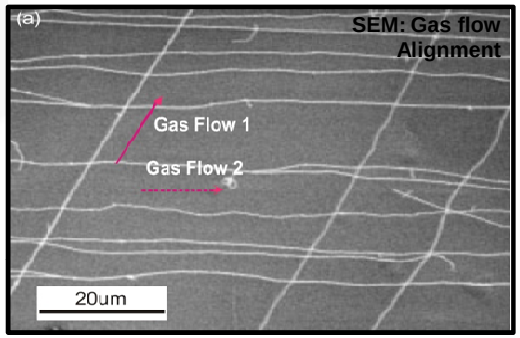
CNT ALIGNMENT MCHANISMS

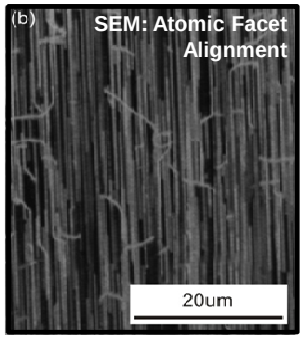


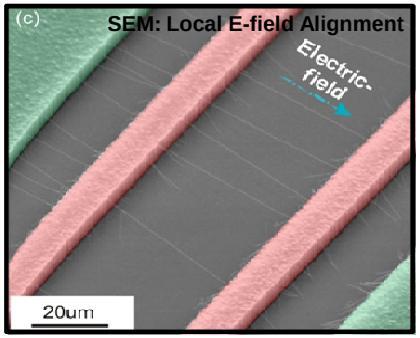


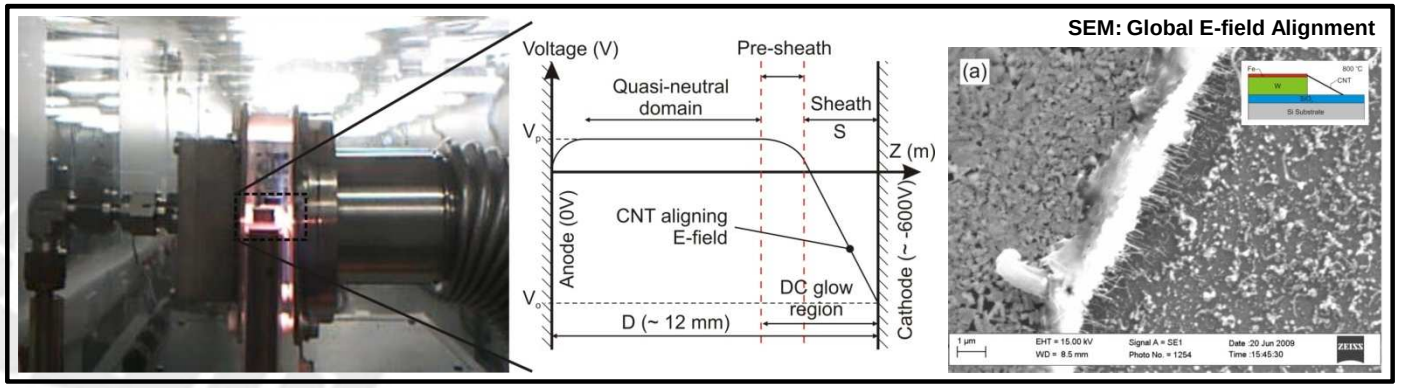








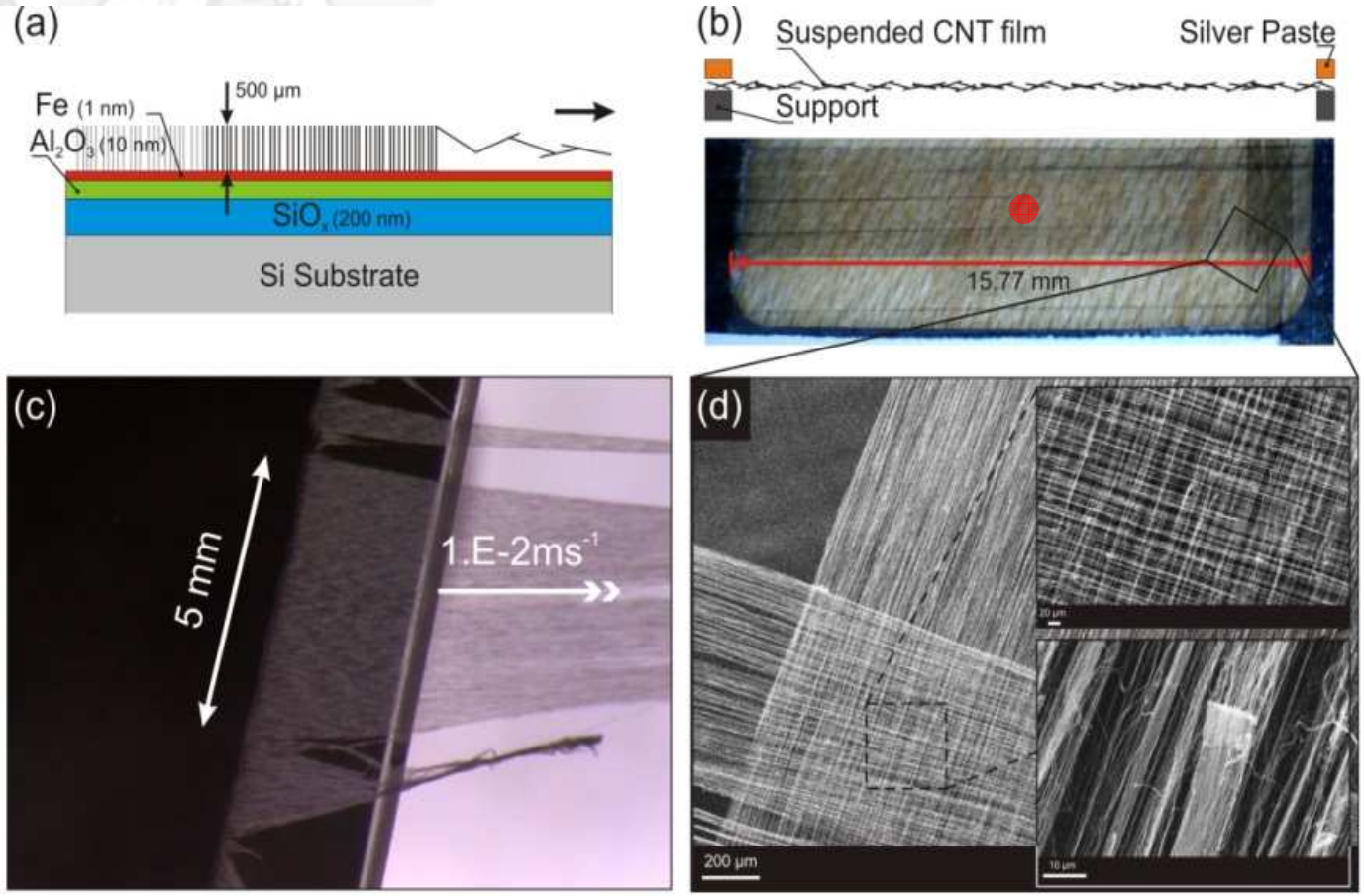




[1] M. Cole, M. Mann, et. al. *unpublished data*
[2] M. Hersam, et. al. *Nat. Nanotech.*, **3** (2008), 387
[3] S. M. Huang, et al., *Adv. Mat.,* ***15*** *(2003),* 19, 1651
[4] C. Kocabas, et al., *Small,* **1** (2005), 1110
[5] Z. Yuegang, et al., *APL,* **79** (2001), 19

C) FULLY SUSPENDED CNT IR SENSOR

- Fabrication
  1. SAMPLE: Si / SiO_2 (200nm) / Al_2O_3 (10 nm) / Fe (1 nm)
  2. VERTICAL FOREST SYNTHESIS: uhp C2H2 : H2 (4%), 700 °c, 25 mbar, 600 s
  3. Pull (rate < 10^{-2} ms^{-1})



C) FULLY SUSPENDED CNT IR SENSOR

- ✓ Incredibly efficient material use
- ✓ 76 %T @ 550 nm
- ✓ $R_{s//}$ = 1.30 kΩ/□
- ✓ $R_{s\perp}$ = 3.75 kΩ/□

} Mean Anisotropy = 2.38

- ✓ Sensitivity = 1.3
- ✓ Bolometric Vs. Photometric?

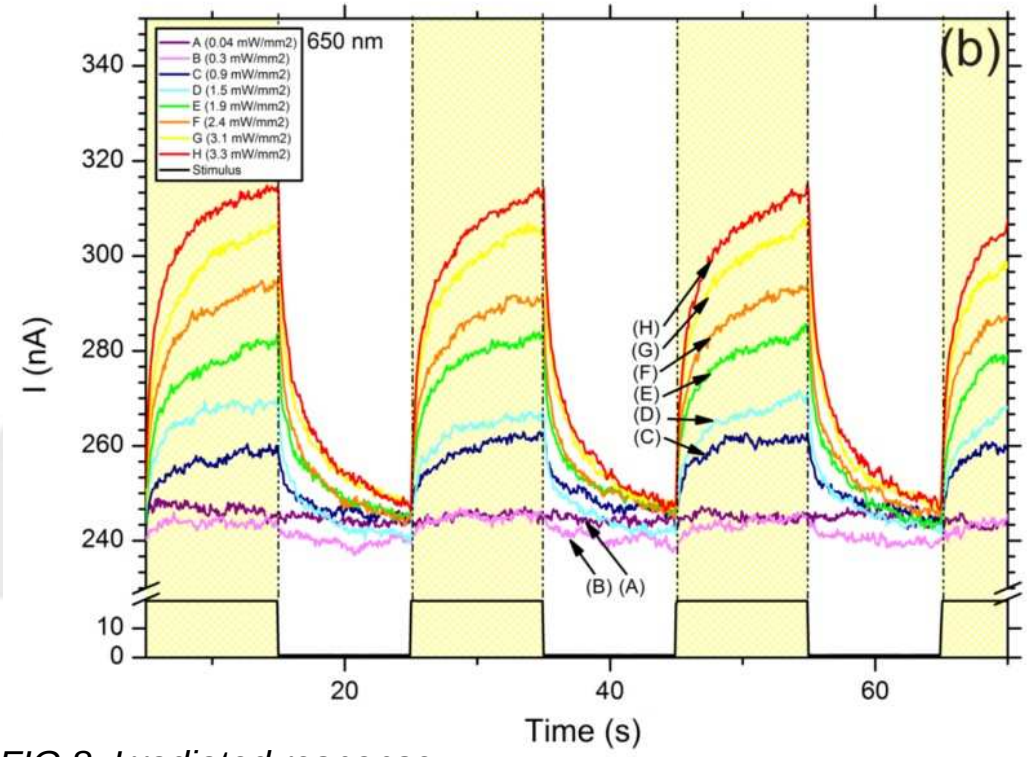


FIG 8. Irradiated response

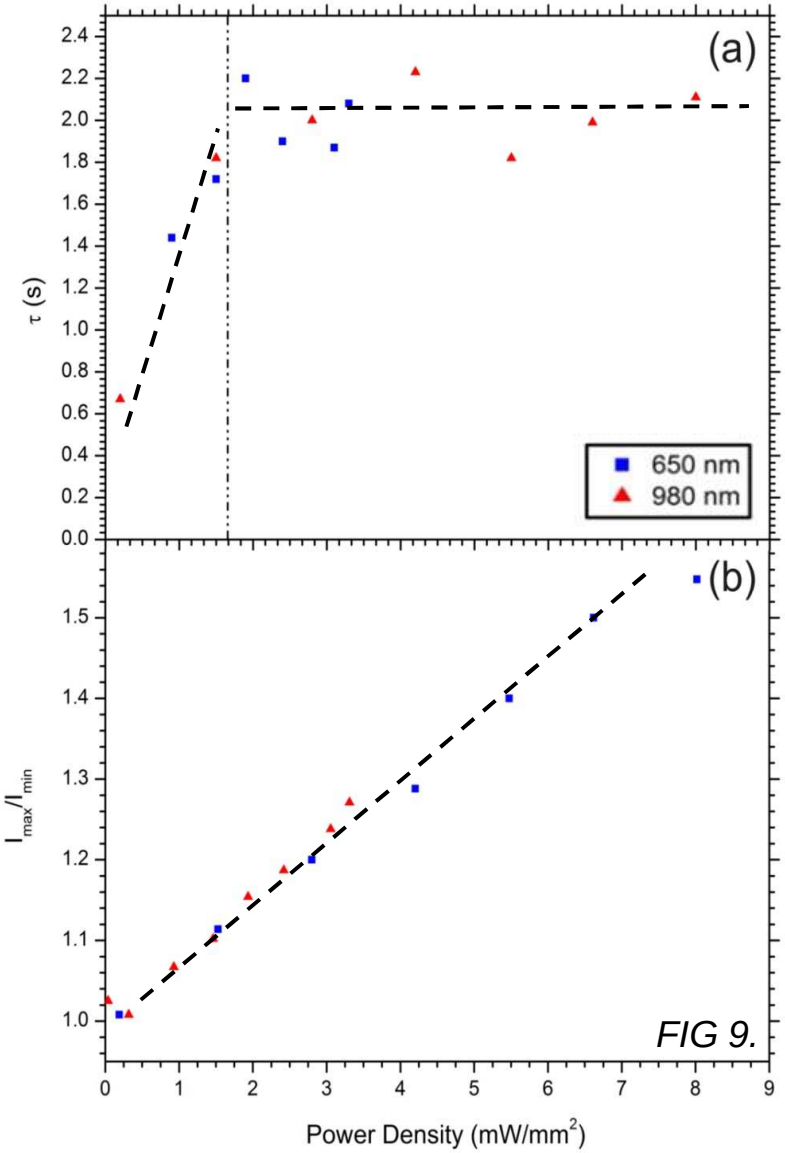


FIG 9.

M. Cole, X. Xu, et. al. submitted

SUMMARY

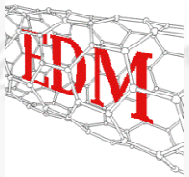
- Binderless flexible CNT film transfer onto PC substrates
  - Highly scalable and inexpensive
  - Low sheet resistance 2.3 Ω/□ @ T_{550} = 10%
  - Potential for controlled transparency
  - Robust to intense mechanical treatment: flexing and strain
  - Strain >30%

- Flexible field emitters based on a variety of CNT films
  - Electrode-less fabrication
  - Low threshold fields (<1.5 V/µm) with high emission currents (mA)
  - Importance of balast resistance to improve uniformity

- Mechanically extruded CNTs
  - High material use efficiency
  - IR response demonstrated (Sensitivity ~ 1.35)
  - Bolometric

ACKNOWLEDGEMENTS

- **People**



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DEPARTMENT OF ENGINEERING

-**Prof. W. I. Milne** (*Group leader*)

- **Y. Zhang**
- **M. Mann**
- **C. Li**
- **P. Hiralal**

HITACHI
Inspire the Next

UNIVERSITY OF CAMBRIDGE
DEPARTMENT OF ENGINEERING

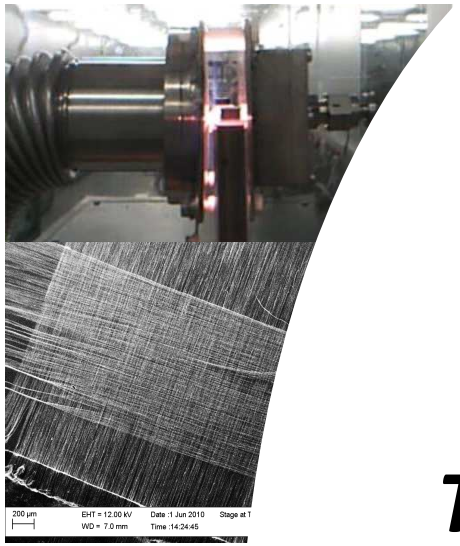
- **X. Xu**

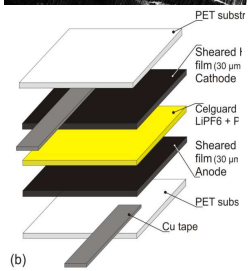
AIXTRON

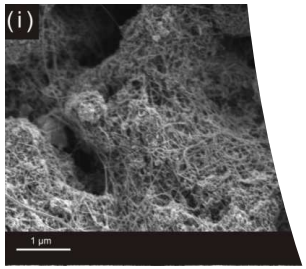
- **K. B. K.Teo**

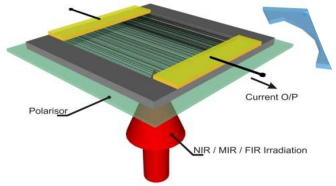
- **Various EC consortia inc.**
  - **AXIS (EU FP7),**
  - **CANDICE, etc (EU FP6),**
  - **EPSRC**
  - **Schiff Studentship, University of Cambridge**
  - **St John's College, University of Cambridge**
  - **Aixtron Nano Instruments**

- **Collaborators**
  - **THALES Research & Technology,**
  - **CNRS / Ecole Polytechnique,**
  - **Fraunhofer-Institut für Siliziumtechnologie,**
  - **National Research Council-Institut Photonics and Nanotechnology,**
  - **York Probe Sources Ltd,**
  - **Xenocs SA,**
  - **Czech Technical University,**
  - **Chalmers University of Technology,**
  - **D'Appolonia S.p.A.,**
  - **Nokia,**
  - **Samsung**









THANK YOU FOR YOUR ATTENTION.

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TNT10
Sep. 2010

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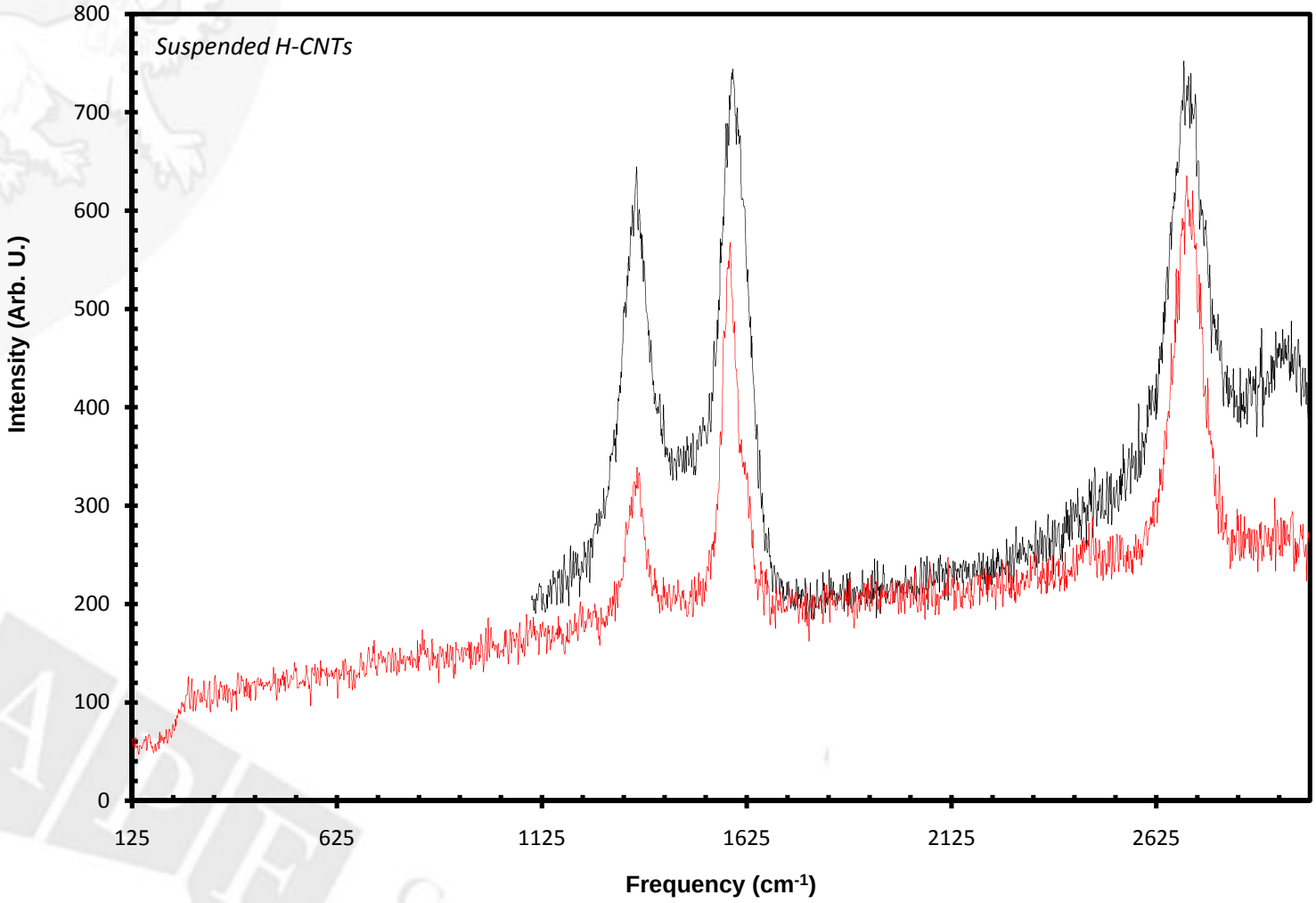
RAMAN DATA


Suspended H-CNTs
Intensity (Arb. U.)
800
700
600
500
400
300
200
100
0
125
625
1125
1625
2125
2625
Frequency (cm-1)