Carbon Nanotube Capture by AC Dielectrophoresis for the Fabrication of a Thin Film Transistor and Investigation of its Properties by Scanning Gate Microscopy

Aren Siekmeier[1 2], Xiaojun Wei[3], Masahiro Matsunaga[3], Yuichi Ochiai[3], and Nobuyuki Aoki[3]

[1]NanoJapan Program, Department of Electrical and Computer Engineering, Rice University, Houston, TX 77005, USA
[2]Department of Physics, University of Minnesota, Minneapolis, MN 55445, USA
[3]Graduate School of Advanced Integration Science, Chiba University, Chiba 263-8522, Japan

Contact Information: Aren Seikmeier ~ siekm008@umn.edu

Single walled carbon nanotubes (SWNTs) are one of many unique materials subject to recent attention due to their remarkable properties, including high electron mobility, flexibility, optical transparency, and chirality dependent electrical properties. Accordingly there has been interest in their application in thin film transistors (TFTs) in the form of random nanotube networks [1]. Considerations for the enhancement of the quality of such a device include the concentrations of metallic and semiconducting nanotubes in the network and the network layout. Deposition of aligned nanotubes has been demonstrated via AC dielectrophoresis (DEP) under certain conditions [2], so we have further investigated the effects of this fabrication technique, using atomic force microscopy (AFM) and scanning gate microscopy (SGM), among other conventional techniques. AC DEP has been shown to selectively capture semiconducting SWNTs from solution, exhibiting much weaker interaction with metallic SWNTs in our experiments. This behavior can be explained by the dependence of the DEP force on the complex dielectric constants of the SWNT and the solution. No significant alignment was achieved with our SWNT samples. Since the torque on SWNTs in an electric field increases with tube length, our average length of 1.6μm might be too small for a substantial aligning torque. We also report on SGM observations and device characteristics of the SWNT network fabricated in this process.

[1] X. Wei, N. Aoki, et al., JJAP, **51**, 04DN05, 2012.
[2] S. Shekhar, P. Stokes, S. Khondaker, ACS Nano, **5**, 1739-1746, 2011.

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[2]Department of Physics, University of Minnesota, Minneapolis, MN, USA
[3]Graduate School of Advanced Integration Science, Chiba University, Chiba, Japan
[4]Department of Electrical Engineering, University at Buffalo, The State University of New York, Buffalo, NY, USA

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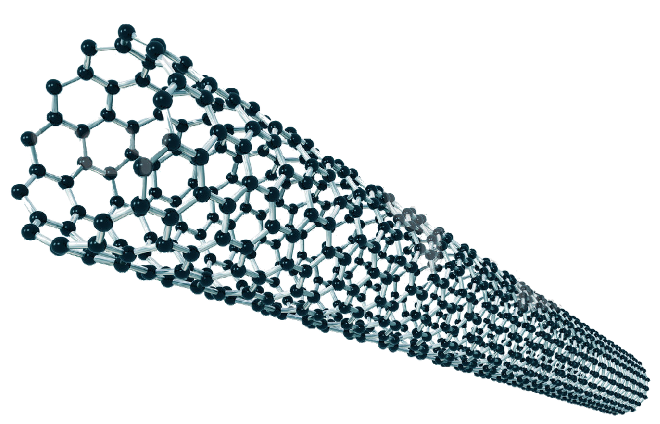
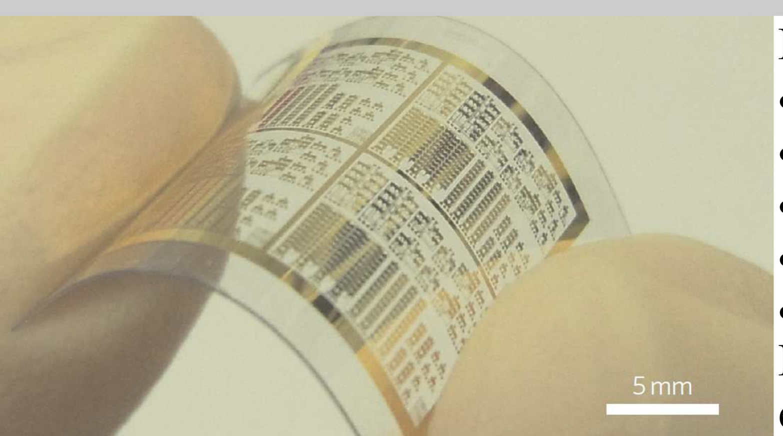
Introduction

Single Walled Carbon Nanotubes (SWNTs)

- Cylindrical molecules of sp^2 bonded carbon
- Low dimensionality
- High electron mobility
- Structure dependent electrical properties
- Optical transparency
- Flexibility
- Mechanical strength



Thin Film Transistors (TFTs)



Features of a SWNT network TFT:

- Low form factor
- High mobility
- Good repeatability
- Uses natural metallicity distribution
- Transparency and flexibility

Many possible applications for future electronic devices.

Motivations

- Responses at M/S junctions desired [1]
- Metallic connections short device
- Current path is indirect

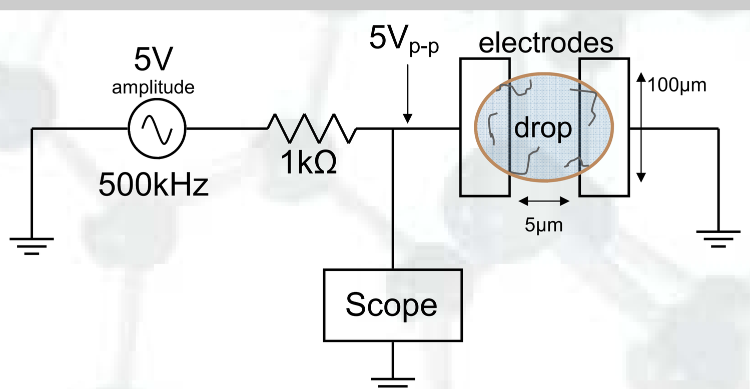
SWNT Layout Manipulation

- Enhance M/S junction density
- Reduce metallic shorts
- More direct current path

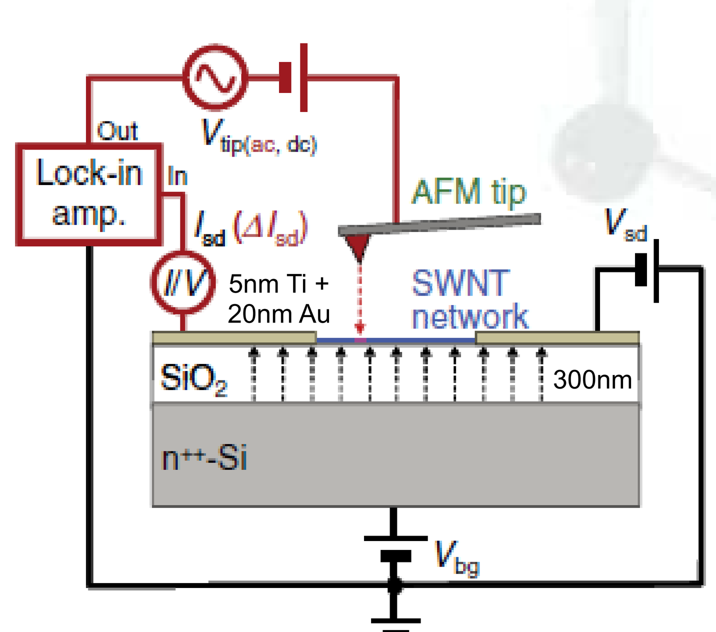
Method

AC Dielectrophoresis (DEP)

- Shown to align high density networks from solution [2]
- SWNTs applied to electrodes, bias applied for 30 seconds to 1 minute
- NanoIntegris sSWNT and mSWNT 90% 1mg/100mL, with surfactant for dispersion
- Methanol treatment to remove surfactant
- Plasma etching to confine channel to 5μm



Scanning Gate Microscopy (SGM)

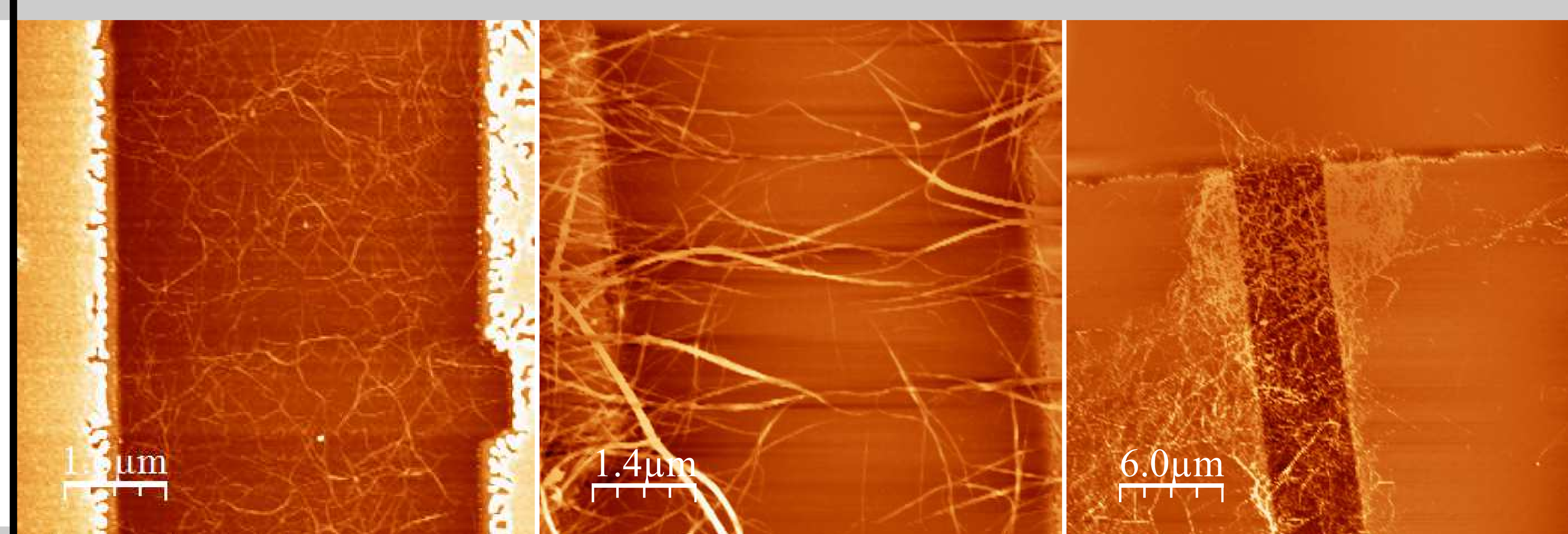


SGM Apparatus

- Mobile point gate scans FET response
- Obtain Atomic Force Microscopy (AFM) and Scanning Gate Microscopy (SGM) images simultaneously
- Locate and characterize FET response [1]

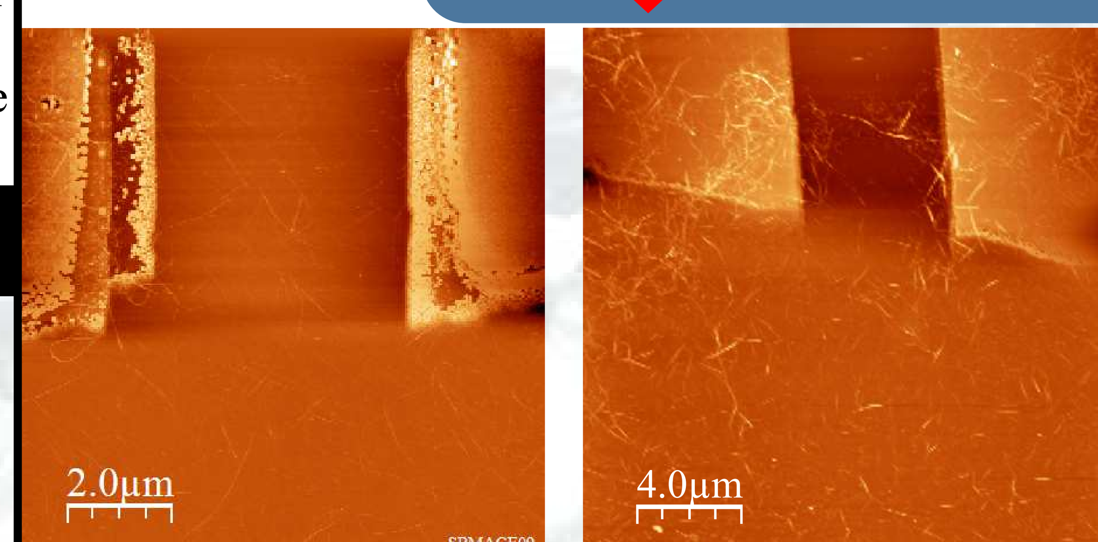
Results and Analysis

AFM of DEP Network



High Density | Alignment | Nanotube capture

Semiconducting vs. Metallic

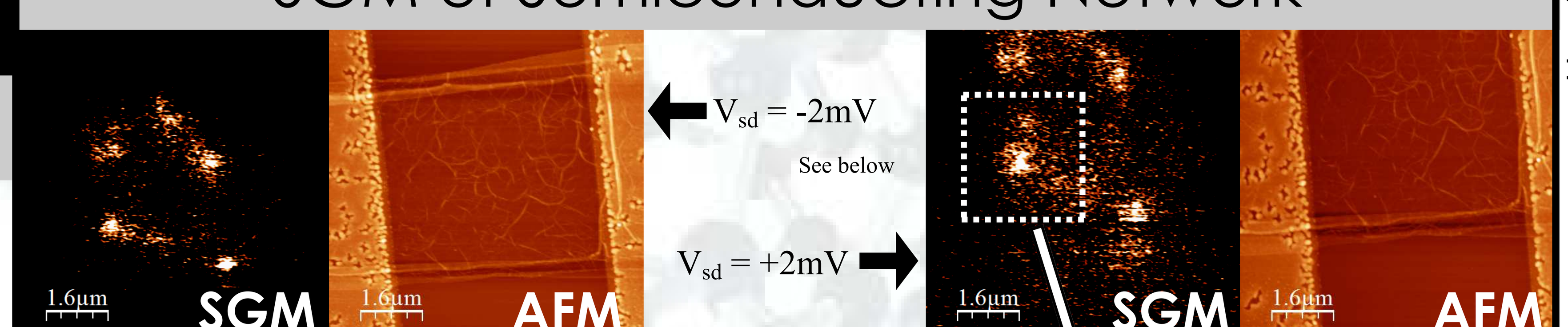


Lower density

No alignment

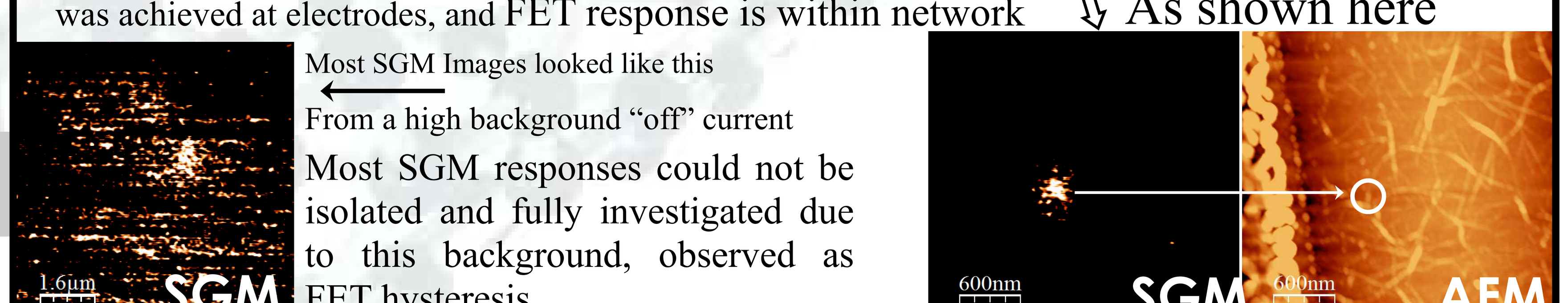
No capture

SGM of Semiconducting Network



Response invariance with change in current direction shows ohmic contact was achieved at electrodes, and FET response is within network

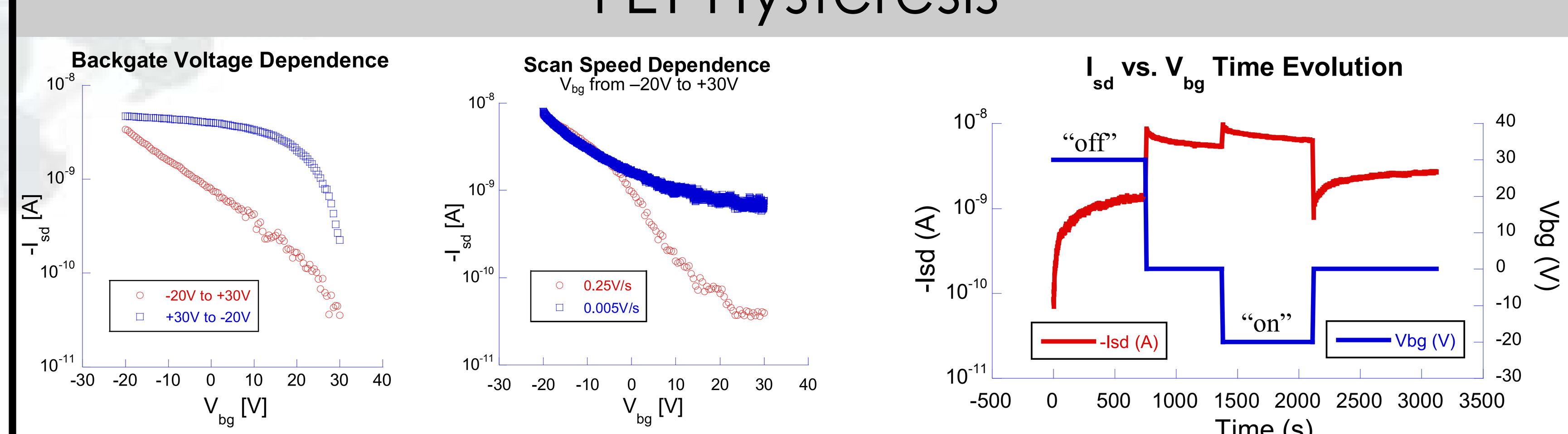
As shown here



Most SGM Images looked like this
← From a high background "off" current

Most SGM responses could not be isolated and fully investigated due to this background, observed as FET hysteresis

FET Hysteresis



FET Characteristic shows large hysteresis
On/off ratio: ~10^2

Slow scan shows higher "off" current over time
On/off ratio: ~10^1

Time evolution of I_{sd} shows good FET performance slowly degrading as current stabilizes
SGM takes time, so is obscured by low on/off ratio

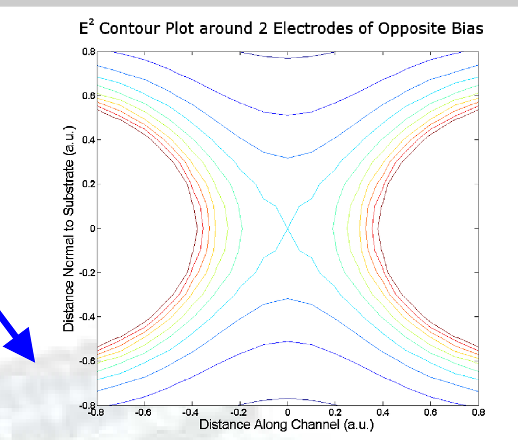
Theoretical Considerations

Capturing and Alignment Mechanisms

$$F_{DEP} \propto \varepsilon_m \operatorname{Re}\left(\frac{\varepsilon_p' - \varepsilon_m'}{\varepsilon_m'}\right) \cdot \nabla |E|^2$$

$$\varepsilon' = \varepsilon - \frac{i\sigma}{\omega}$$

Clausius Mossotti factor
Complex dielectric constant determines attraction or repulsion



$$\begin{pmatrix} P_x \\ P_y \\ P_z \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \varepsilon_\parallel & 0 & 0 \\ 0 & \varepsilon_\perp & 0 \\ 0 & 0 & \varepsilon_\perp \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} E_x \\ 0 \\ 0 \end{pmatrix}$$

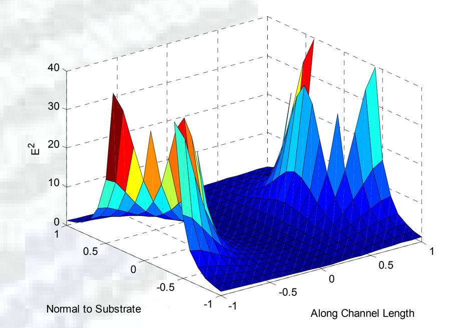
$$\vec{\tau} = \vec{P} \times \vec{E} = \begin{pmatrix} 0 \\ 0 \\ -P_y E_x \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \sin\theta \cos\theta (\varepsilon_\perp - \varepsilon_\parallel) E_x^2 \end{pmatrix}$$

$$\tau_z = \frac{1}{2} \sin 2\theta (\varepsilon_\perp - \varepsilon_\parallel) E_x^2$$

Torque on nanotube in an electric field from anisotropic permittivity

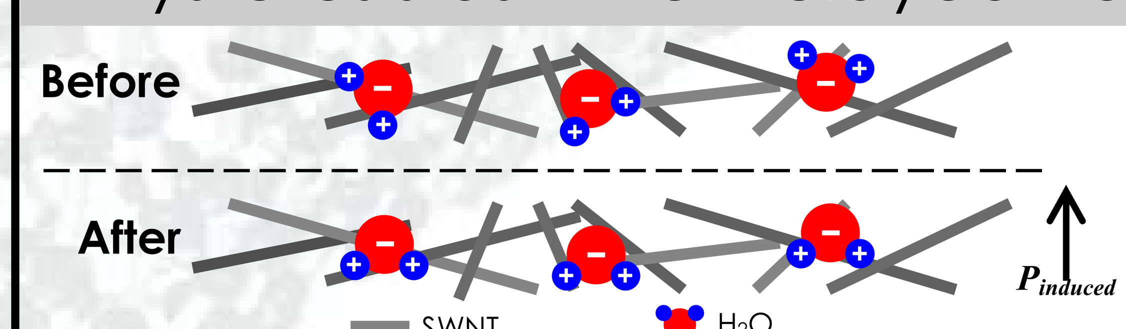
Alignment requires: $\varepsilon_\parallel - \varepsilon_\perp >> 0$ Which grows with L^2 [3]

Nanotubes too short for observable alignment or high density obstructs it



Particles move to regions of higher field magnitude, resulting in observed capturing

Hysteresis as Time-Delayed Polarization



Hysteresis could arise from slow polarization ($P_{induced}$) of water trapped in network, screening out backgate effect (E_{ext}) on nanotubes

Conclusions and Future Work

⇒DEP selectively captures SWNTs, no alignment
⇒FET response within SWNT network

More Investigation of:

⇒Solution concentration, deposition parameters
⇒Network Composition (Raman spectra, etc.)
⇒Hysteresis: Avoidance or Exploitation

Towards Our Pie in the Sky...

High Quality TFT

Acknowledgements

This work was conducted in the Ochiai-Aoki Lab at Chiba University through the NanoJapan program, sponsored by Rice University and NSF PIRE. This work was also funded by Grants-in-Aid for Scientific Research from JSPS. We would also like to recognize the collaboration of Professor Jonathan P. Bird (University at Buffalo).

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[1] X. Wei, N. Aoki, et al., "Analysis of Operation Mechanism of Field Effect Transistor Composed of Network of High-Quality Single Wall Carbon Nanotubes by Scanning Gate Microscopy," JJAP, **51**, 04DN05, 2012.
[2] S. Shekhar, P. Stokes, S. Khondaker, "Ultrahigh Density Alignment of Carbon Nanotube Arrays by Dielectrophoresis", ACS Nano, **5**, 1739-1746, 2011.
[3] Ma Shao-Jic, Guo Wan-Lin, "Mechanism of Carbon Nanotubes Aligning along Applied Electric Field," Chin. Phys. Lett., **25**, 270-273, 2008.

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